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Monitored Performance of Residential Geothermal Heat Pumps in Central Texas and Southern Michigan

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Monitored Performance of Residential Geothermal Heat Pumps in Central Texas and Southern Michigan

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Abstract

This report summarizes measured performance of residential geothermal heat pumps (GHP's) that were installed in family housing units at Ft. Hood, Texas and at Selfridge Air National Guard base in Michigan. These units were built as part of a joint Department of Defense/Department of Energy program to evaluate the energy savings potential of GHP's installed at military facilities. At the Ft. Hood site, the GHP performance was compared to conventional forced air electric air conditioning and natural gas heating. At Selfridge, the homes under test were originally equipped with electric baseboard heat and no air conditioning.

Installation of the GHP systems at both sites was straightforward but more problems and costs were incurred at Selfridge because of the need to install ductwork in the homes. The GHP's at both sites produced impressive energy savings. These savings approached 40% for most of the homes tested. The low cost of energy on these bases relative to the incremental cost of the GHP conversions precludes rapid payback of the GHP's from energy savings alone. Estimates based on simple payback (no inflation and no interest on capital) indicated payback times from 15 to 20 years at both sites. These payback times may be reduced by considering the additional savings possible due to reduced maintenance costs.

Results are summarized in terms of 15 minute, hourly, monthly, and annual performance parameters. The results indicate that all the systems were working properly but several design shortcomings were identified. Recommendations are made for improvements in future installations at both sites.

Acknowledgments

This program was funded as part of the joint DOE/DoD Strategic Energy Research and Development Program (SERDP). The thoughtful guidance and fiscal support offered by Lew Pratsch of the DOE throughout this program is gratefully acknowledged.

The Ft. Hood project would not have materialized without the initial suggestion generated by John Brewer of Central Texas College in Killeen, TX. John coordinated the first meetings between the author, Bobby Lynn of Ft. Hood, Ralph Cadwallader of Loop Tech International, Charles Smith of Accurate Air systems, and Ralph Schroeder of TU Electric. Various meetings and the individual contributions of these collaborators eventually led to the successful planning and implementation of the Ft. Hood GHP demonstration.

The Selfridge site was identified by Thelma Dobson of Detroit Edison who arranged the initial meetings between the author, Ron Wesley and Rodney Wilson of Selfridge, Rich Lavack of R & L Heating and Cooling, Lee Barker of LoopTech, Rob Derkson of WaterFurnace, and Bob Pratt and Jerard Goetz of Detroit Edison. This team rapidly produced an excellent design which was accepted by Selfridge and delivered in a timely, effective manner.

The author would like to thank Gary Phetteplace of the Army Corps of Engineers Cold Regions Research Engineering Laboratory (CRREL) for his participation in the design reviews and his design suggestions.

Finally, thanks are due to Bob Meyer of Sandia for his help in coordinating the data acquisition system design and in compiling results.

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Monitored Performance of Residential Geothermal Heat Pumps in Central Texas and Southern Michigan

Introduction and Summary

The geothermal heat pump (GHP) is a concept for heating and cooling buildings more efficiently. The idea is based on the observation that for most regions of the country, the near-surface ground temperature (depths from 10 to 500 ft) is nearly constant year round and fairly close (50 to 70 °F) to the desired temperatures for building interiors. With a reversible heat pump exchanging heat between the near-surface ground and the building interior, the building may be heated or cooled very efficiently because of the relatively low temperature difference between the building interior and the ground.

This is a very simple concept that requires some mechanism to thermally connect the heat pump to the below-surface geology. A variety of techniques may be used to accomplish this [1]*. The simplest are so-called open loop systems which use pumped well water passed through the heat pump's water-to-freon heat exchanger. After the groundwater exchanges its heat with the GHP, it is then discharged to the surface or reinjected back to the aquifer. These systems work well but can only be used in areas with plentiful water resources which are not limited by other regulatory constraints. Unfortunately, in many communities lack of water resources or restrictions on water disposal will preclude the use of open loop systems.

There is a closed loop alternative which avoids the problems with open loops. In typical closed loop systems, a fixed quantity of fluid (usually water or anti-freeze) is circulated between the heat pump water-to-freon heat exchanger and a circuit of pipes which are buried in the ground and in intimate thermal contact with the local geology. This permits transfer of heat from the geology to the pipe and its circulating fluid by thermal conduction. The pipe in a closed loop system may be buried in trenches, vertical boreholes, or even submerged in ponds or streams. In general, because the thermal conductivity of the earth is relatively low, a substantial length of pipe (750 to 1500 ft for a typical, 1500 sq. ft. residence) must be buried meet the heat transfer demands of the heat pump. Closed loop systems may be installed in just about all locales in the US provided the building has sufficient land area for the vertical boreholes or trenches and that drilling or excavation conditions are reasonable. Because of the widespread applicability of closed loop designs, they are the most common type of GHP systems being installed in the US even though open loop designs are usually less expensive (because less excavation is needed) and more efficient [2].

As part of a joint Department of Defense (DoD) and Department of Energy (DOE) project to encourage the use of new, energy efficient and renewable energy technologies on DoD installations, Sandia initiated a number of demonstration and/or monitoring projects of closed loop GHP installations at Ft. Polk, LA, Patuxent River Naval Air Station, MD, Dyess Air Force Base, TX, Ft. Hood, TX, and Selfridge Air National Guard base, MI.

* Numbers in brackets denote references listed at the end of this document.

This report covers test results for two years of monitoring the performance of residential GHP's at Ft. Hood and Selfridge. These demonstrations had a variety of objectives:

1. Give base personnel hands-on experience with this technology at their facility.
2. Conduct a thorough engineering evaluation of the installed demos to determine their effectiveness and energy savings potential.
3. Advise base personnel of lessons learned and issues to consider for any future, larger GHP conversion projects.

This report will focus on the results of the engineering evaluation and energy monitoring efforts which began when the systems were first installed. The data acquisition continued at both the Texas and Michigan sites for approximately two years.

The demonstration homes at both Ft. Hood and Selfridge consisted of ranch style duplexes which were built in the 1960's. The individual family housing units consist of modest, 3 or 4 bedroom layouts with 1000 to 1200 sq. ft. of living space. The homes at both sites have been well maintained and most have received a number of improvements to windows, insulation, and other mechanical systems.

Local engineers and contractors designed the GHP retrofits for these buildings. At both sites, design and construction was effected by personnel who were experienced and comfortable with GHP installations at similar sites.

The energy savings possible from using GHP's compared to other heating, ventilating and air conditioning (HVAC) options are readily estimated, based on manufacturer's data on HVAC hardware performance, thermal models for the ground loop or open loop source, local weather data, and a model for building thermal loads. Although energy savings calculations accompany most GHP designs, there are surprisingly few installations where long-term measurements have been made to confirm the savings estimates. The sites studied in this report are particularly well-suited for determining savings because the conventional HVAC can be compared with GHP's in otherwise identical duplexes. The reader should be cautioned, however, that there are substantial residence-to-residence variations in energy use due to occupancy effects which were not controlled in this study. Although the sample size (3 GHP homes and 3 conventional at each site) is much too small to use for generating "average" savings which are statistically significant, we do believe the results are indicative of the savings possible with similarly installed and operated GHP systems. The reader is referred to a recently published report [5] on the performance of 4000 GHP residences at Ft. Polk, LA for more statistically significant data on residential GHP performance.

The as-built GHP systems tested offered excellent comfort and impressive (usually 40% or more) HVAC energy savings at both sites. There were differences in the ease of installation at the two locations. The GHP installations at Ft. Hood were straightforward because they used existing building ductwork and drilling conditions were excellent. Quite the opposite was true at Selfridge, where the GHP homes needed all new ductwork and drilling proved to be difficult and expensive. Because of these differences in installation difficulty and cost, Ft. Hood would be the best candidate for additional, widespread conversion of similar subdivisions or construction of new residences with closed loop GHP HVAC systems.

Unfortunately, the low utility rates currently being paid at these bases and the high retrofit costs indicate a slow (greater than 10 years) payback from energy savings alone for this conversion. Some design improvements are suggested based on the measurements which should improve the payback and performance of similar future retrofit installations.

Ft. Hood Demonstration

Site Characteristics

Ft. Hood is located in central Texas adjacent to Killeen, TX. It is about 60 miles directly north of Austin, TX. The climate is hot and humid in the summer (design cooling air temperature of 100 °F dry bulb, 74 °F wet bulb) and moderate in the winter (design heating air temperature of 20 °F dry bulb). Based on 10 year average temperature data [3] the site has 2000 cooling and 2300 heating degree-days per year.

The test homes are located in the Montague subdivision on the southwest portion of the base. This subdivision consists of hundreds of duplexes built in the 1960's. A typical unit is shown in Figure 1. Construction is wood frame on a concrete slab foundation.

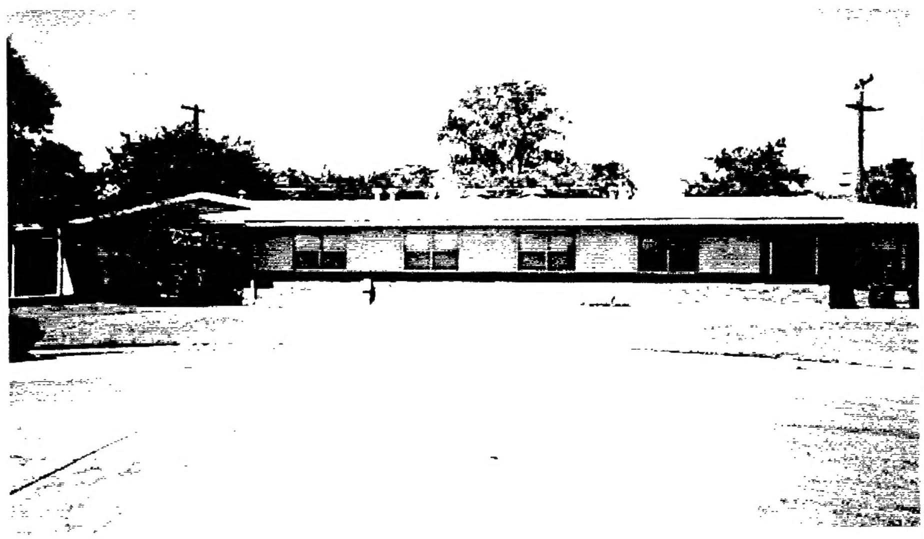

Figure 1. Typical duplex residence in the Montague subdivision at Ft. Hood

The duplexes in this area are on roughly 1/4 acre rectangular lots, and the subdivision has a number of parks and open areas. All the lots have simple landscaping with grass and some small shrubbery. The site is mostly flat, though there are gently rolling hills in the area.

All the housing units are equipped with a gas forced air furnace (75,000 Btu/hr heat input) and 2.5 ton nominal air source central air conditioners. The air conditioning units appeared to have been added after the homes were built because wiring to the condenser/compressor assembly was by conduit added outside the buildings. We estimate that the furnaces and air conditioners were at least 20 years old.

The furnace/air handler is located in a central utility closet for each housing unit. Insulated rigid ductwork in the attic distributes conditioned air throughout the house. There is a single, large return air grill beneath the utility closet door.

From this subdivision, base personnel selected three duplexes located on the same street for testing. Each of the test homes have slightly different floor plans, shown in Figure 2. One of the units (#1) is a three bedroom (1200 ft.^{2}), and the others are two bedroom (1000 ft.^{2}). For each duplex, one half was

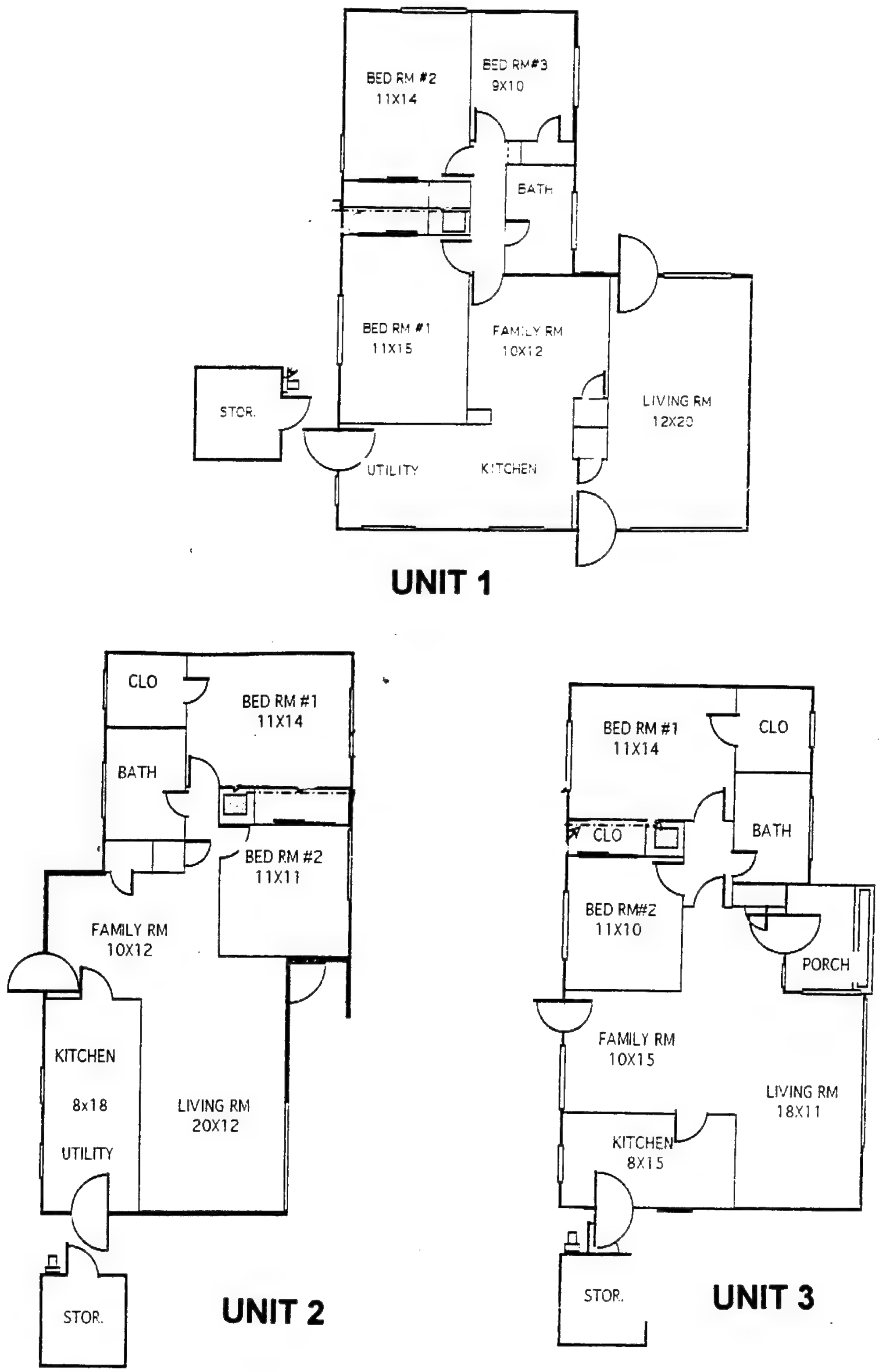

Figure 2. Floor plans for the GHP converted units

slated for retrofit to the geothermal heat pump and the other half left alone except for addition of instrumentation.

There have been no geothermal heat pump systems previously installed at Ft. Hood, so information on below surface geology was limited. A few units installed at Central Texas College nearby indicated that the site would consist of soft limestone with occasional clay seams. Groundwater was not expected at the depths typical for ground loops (250 ft or less).

System Design

The GHP systems were jointly designed by Charles Smith of Accurate Air Systems (Houston, TX), Ralph Cadwallader of Loop Tech International and John Brewer of Central Texas College. This team had designed and installed a number of residential GHP systems in the region and were thoroughly familiar with the technology. The designers were asked to produce a "typical" GHP design but to lean toward a conservative approach, which ensured high reliability and efficiency, rather than designing a minimum cost system.

Following a walk-through in March, 1994 with base personnel, the designers determined that packaged vertical flow heat pump units could be installed as drop-in replacements for the original furnace/air handler in the utility closet. This required fabricating special ductwork transitions to fit the supply air outlet of the heat pump to the original ductwork and using an existing utility chase under one of the bedroom closets for routing the ground loop headers to the heat pump.

Heat recovery (desuperheaters) systems are an optional feature of most heat pumps which can augment the domestic hot water supply while reducing some of the thermal load on the ground loops. These systems were not seriously considered for this project because the gas fired hot water heaters in these homes are located in the kitchens, far from the HVAC utility closet. Because the homes were built on slab foundations, the only reasonable way to plumb a heat recovery system would be through the attic which would be subject to freezing. If not for this issue, heat recovery would have been used and we believe it would have been quite effective in this climate.

Load calculations following ACCA Manual J [4] were conducted by the designers. For the larger test home (unit 1), these calculations yielded a design cooling gain of approximately 28,000 Btu/hr and heating loss of 37,000 Btu/hr. The smaller test homes (units 2 and 3) indicated a cooling gain of 24,000 Btu/hr and heat loss of 33,000 Btu/hr.

The designers selected heat pumps from the WaterFurnace AT series based on their familiarity and confidence with these systems and their availability in the area. These units are considered high efficiency relative to most GHP systems. They have an energy efficiency ratio for cooling (EER) of 16 and coefficient of performance (COP) for heating of 3.5. The EER is defined as the ratio of heat removed in Btu/hr to power needed in watts and the COP as the ratio of the rate of heat supplied to the home in watts to the power supplied to the heat pump (watts). Because of the different loads in the family housing units, the designers choose a larger unit (AT 034) for unit 1 and a smaller one (AT 028) for units

2 and 3. These units have a cooling capacity of 32,000 and 27,000 Btu/hr, respectively, at loop temperatures of 90 °F, and are adequately sized to remove the design heat gain. Their heating capacity is similar (32,000 and 27,000 Btu/hr for loop temperatures of 50 °F) and is not quite equal to the design heating load. For this reason, 5 kW of resistance heat was specified, which adds an additional 17,000 Btu/hr of heating capacity to these units.

Because of the limited space and ground water availability in this subdivision, it was decided to design a vertical, closed-loop system. The ground loops were initially designed using proprietary software from WaterFurnace referred to as WFEA (for WaterFurnace Energy Analysis). The basic calculations made in WFEA are probably similar to the CLGS (Closed Loop Ground Source) software documented in [1] but WFEA has additional features to make it easier for the designers to use. WFEA is basically a "temperature bin" design package, which allows the user to enter building loads, weather data, loop lengths, local geology, heat pump type, etc. The software generates loop temperatures, GHP duty cycle, energy consumption, etc., for each 5 °F wide temperature bin.

In designing the ground loops, the following assumptions were made:

1. Bin type weather data from Waco, TX.
2. The soil conductivity assumed to correspond to "Average Rock", or 1.2 Btu/hr/ft/F.
3. Loop temperatures between a maximum of 95 °F (summer) and a minimum of 50 °F (winter).
4. Undisturbed ground temperature of 70 °F.

These assumptions yielded a design with total bore length of 660 ft for the larger housing unit and 600 ft for the two smaller ones. The designers chose to obtain this length with three bores on 15 ft centers for each housing unit, the exact placement to be determined. A spreadsheet summary for the predicted performance of the larger system design is given in Table 1.

There was a design review for this project held at Ft. Hood in September 1994 to finalize details prior to start of construction. This review produced only one major design change: The total bore length for each unit was increased to 750 ft. This was done to increase design conservatism and to simplify the installation, since all housing units would have the same ground loop design, consisting of three 250 ft bores.

Installation

Letters were sent to the residents of the homes to be tested to inform them about the project and the impact that the construction would probably have on their homes and the neighborhood. The installers planned their work so it could be done quickly and with minimal inconvenience to the residents. As it turned out, the installations were straightforward and all work was completed in a week and a half. There were no complaints voiced by any of the residents about the installations.

Installation was begun in early October, 1994. A relatively light weight (25,000 lb.) top drive single axle drilling rig owned by Loop Tech International (Figure 3) was used for loop installation. The intention

WEATHER		GHP SYSTEM			
AIR TEMP °F	ANN. HOURS	EST. LOOP TEMP °F	GHP OUTPUT (Btu/hr)	EST. LOAD (Btu/hr)	GHP DUTY CYCLE (%)
112	0				
107	3	97	31,757	31,179	98
102	60	93	32,212	27,741	86
97	258	89	32,662	24,303	74
92	458	86	33,108	20,864	63
87	608	82	33,549	17,426	52
82	827	78	33,986	13,987	41
77	1082	75	34,419	10,549	31
72	987	71	34,847	7,111	20
67	851	69	35,099	5,076	14
62	715				
57	650	70	-40,470	-1,708	4
52	621	68	-39,593	-5,100	13
47	557	66	-38,717	-8,401	22
42	450	64	-37,842	-11,883	31
37	313	62	-36,968	-15,275	41
32	184	60	-36,095	-18,667	52
27	78	58	-35,222	-22,058	63
22	34	55	-34,351	-25,450	74
17	17	53	-33,481	-28,842	86
12	5	51	-32,613	-32,233	99
7	0				

Table 1. WFEA predicted performance for unit 1 with 660 ft. loop

was to use a technique called "air drilling". With this technique, drill cuttings are brought up the annulus between the bore and the drilling rod by a stream of compressed air supplied by the rig. This is a much cleaner alternative than the more conventional mud drilling method, but the formation must be relatively dry and stable for air drilling to work. Fortunately, air drilling worked very well for all the bores at this site.

The major environmental impact of air drilling consists of dust generation, mechanical noise from the compressed air and the drilling rig, and generation of cuttings at the surface. Fortunately, the noise and dust problem was limited because the rig drilled so quickly that only a few hours drilling were needed at each site. To facilitate clean-up, cuttings were collected on a plastic sheet on the ground surrounding the bore, and most of the cuttings were used as back fill by shoveling them back into the bore after loop insertion. In compliance with local code requirements, the top ten feet of the bore was treated with dry bentonite grout. This process yielded a very clean site, as shown by Figure 4. This figure shows three completed bores with the 1" polyethylene U-tube ends exposed prior to headering. The construction damage to this yard is minimal, just mild tire depressions left by the drill rig in the lawn.

The three bore loop fields at each residence were connected in parallel to 1.5" supply and return headers with socket fusions. Narrow 24" deep trenches made with a small chain trenching machine were used for the headers. Three-way polyethylene purge and fill valves were installed on the loop headers and placed below ground in a sprinkler control box next to the exterior wall of the home. The loop headers actually

Figure 3. Drilling operation at Ft. Hood

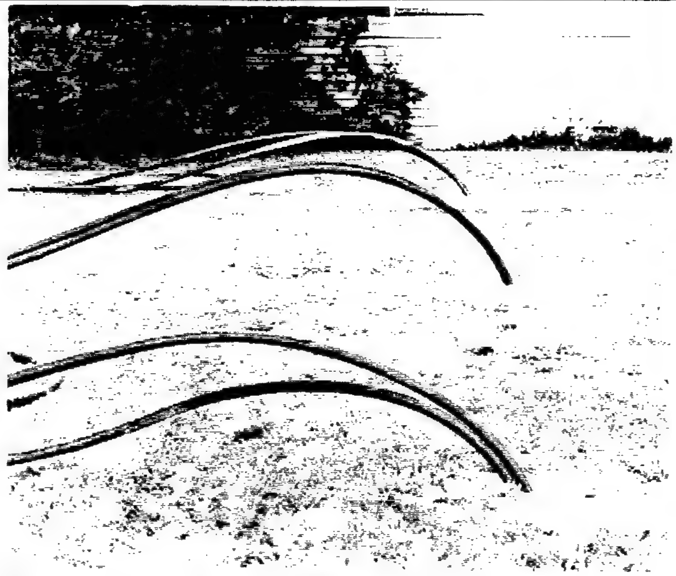

Figure 4. Loop ends before headering.

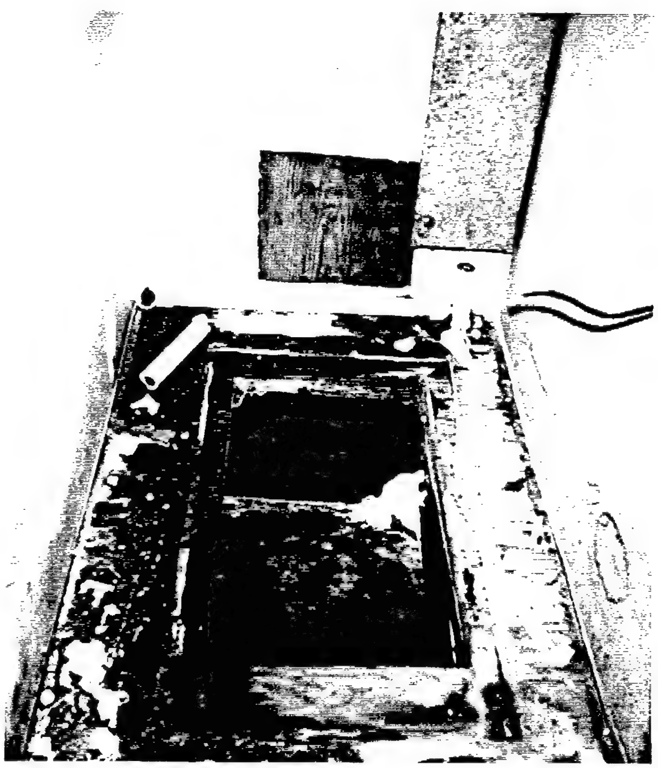

Figure 5. Utility closet with original furnace/air handler removed.

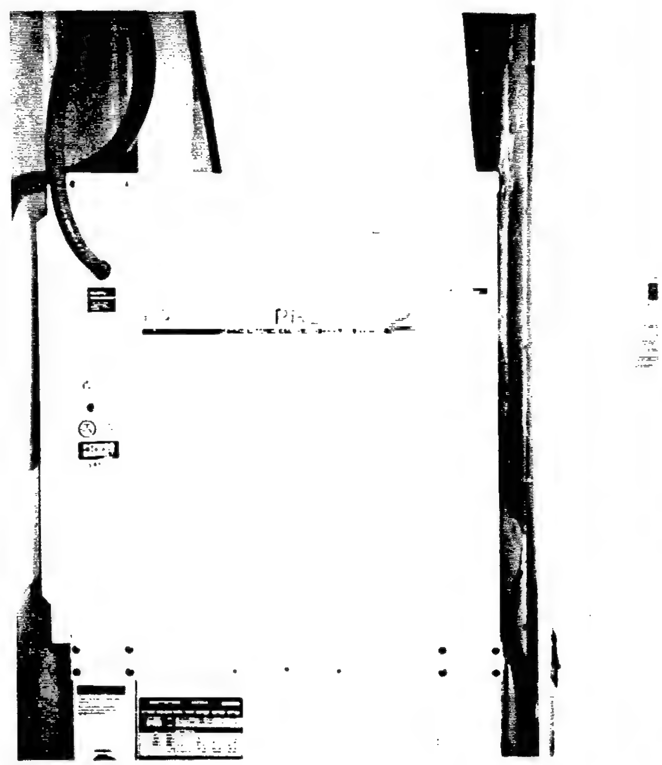

Figure 6. WaterFurnace GHP unit installed in utility closet.

entered the home just above grade through the framed walls to avoid penetrations through the slab foundation. The loop fields and the associated headers and valves were installed for all three test homes in about four working days. All of the loop fields were completed prior to installation of the heat pumps inside the buildings.

Because the residences were occupied, the HVAC contractor planned his installation so that removal of the original systems and replacement with the heat pumps could be completed with no more than 24 hours down time to the home's HVAC system. The contractor achieved this goal, but had to work hard to do it. Most installation difficulties were caused by the limited space in the utility closets (Figure 5). The heat pump units were shorter than the original furnace/air handlers, but considerably wider. This resulted in tight clearances and a lack of working room in the closet. Figures 6 shows the heat pump unit installed in one of the homes. Although the side clearance is minimal, normal servicing of the unit is through the front panel which is readily accessible.

Instrumentation and Data Acquisition

The instrumentation system used for this project was designed, installed and maintained by John Brewer of Central Texas College A most important measurement was also contributed by TU Electric, the local utility, who measured and compiled electrical use data for all six homes. The TU Electric data consisted of monthly whole-house energy consumption and detailed, 15 minute demand data for the GHP and conventional AC systems.

The 15 minute demand data for the HVAC systems were acquired through storage meters on circuits dedicated to the GHP or the outside condenser unit for the conventional AC hardware. The GHP energy monitoring circuit included the loop pump and all electrical loads interior to the GHP unit, which includes the air handler fan, compressor, resistance heaters, and control hardware. The conventional AC energy monitoring included all hardware located within the condenser unit, including the condenser fan, compressor, any outdoor controls, etc. Not included with the AC system monitoring is the energy consumed by the interior air handler. The fan power is estimated to be approximately 500W. Some small corrections were made to the energy measurements presented in this report to account for this unmeasured blower energy.

The design intent of the instrumentation system was to allow assessment of the engineering performance of the heat pumps and loop systems, to determine energy savings, to be transparent to the residents, and to be maintainable and reliable over the two year period of this test.

The basic technical measurements planned for the GHP system were entering and leaving loop temperature, supply and return air temperature, two measurements of outside air temperature, and the on/off state of the compressor, auxiliary resistance heat, and the reversing valve. For the conventional homes, we measured supply and return air temperature, and the on/off state of the AC compressor and the 24V gas furnace valve. After the initial planning, two additional channels were added to measure the hot gas discharge temperature of the GHP and AC compressors. Also, the reversing valve measurement was dropped because the GHP direction (heating or cooling) could easily be determined from air or water temperature differences.

A simple approach to data acquisition and storage based on the SmartReader data logging card, manufactured by ACR Systems, Inc., was selected. The SmartReader is a small, battery powered logger which stores 7 channels of time/date stamped averaged data with a user selected averaging interval (averages ranging from 5 minutes to 1 hour). The unit can retain up to 33Kb of data digitized through an 8 bit A/ D converter. Two cards were used for each duplex, one card monitoring the GHP and the other outside air temperature and the conventional AC and gas furnace.

As a partial backup to the SmartReader system, power to the compressors, resistance heaters and gas demand valve were connected to accumulating run time meters that were read at least monthly.

Instrument leads for all the channels were routed from the home interiors to a weatherized and locked box placed outside the homes. With this setup, all downloading could be done outside the home without disturbing the residents. SmartReader cards were downloaded every two weeks or once a month, depending on the sampling rate.

The SmartReaders used two different averaging intervals over the two year test period. For the first 3 months of testing, a 5 minute interval was used to ensure capture of HVAC short cycling or other transient effects. This short interval, however, required downloading the SmartReader cards every 14 days and generated a huge amount of data to analyze and catalog. After the first three months, it was apparent that the HVAC systems were functioning properly, the averaging interval was increased to 20 minutes and the downloading conducted monthly.

The raw SmartReader data was converted to ASCII tabular data using software supplied by the manufacturer. The data for each test duplex, which used two SmartReaders, were then combined into a single Excel spreadsheet for archival and post processing. The archived data consist of a spreadsheets covering one calendar month of data for each duplex. These raw data were post processed in a variety of ways to be discussed and presented below. The most common processing consisted of compression to hourly or monthly averages and identifying monthly maxima or minima.

The data acquisition system proved to be reasonably reliable over the two year test period. There was some data lost due to poor or broken connections of the instrument leads into the SmartReader cards, relay failures, and failure of two of the SmartReader cards towards the end of the program. Data retention, in spite of these problems, was better than 95%.

The process of manually downloading, reviewing, archiving, and post processing the data proved to be labor intensive and required a great deal of care to avoid errors in channel assignments, dates, etc. This process became faster and more accurate as the routine was established, but it still needed at least a half day of professional time to review and archive data from each download.

Testing Results

Startup problems

Data acquisition began in November, 1994 shortly after the three GHP units were installed, but the on/off relay channels were not fully functional until late February, 1995. All three of the GHP systems provided

reliable heating and cooling immediately after installation but early data acquired indicated some startup problems.

Unit 1, the larger GHP unit, indicated a relatively large loop temperature difference in heating mode (15 °F instead of 8-10 °F for units 2 and 3). The measured temperature difference for unit 1 suggested a loop flow rate through the heat pump of about 3 GPM. This is lower than the manufacturer's recommended minimum of 5 GPM. Inspection of the heat pump showed that a loop ball valve was not fully open and that the installed pump had marginal capacity. This problem was corrected in late December by installing another pump in series with the existing pump and fully opening the ball valve.

A more serious problem was observed with unit 3 in late December when a fault in the heat pump microprocessor disabled the compressor, although the heat pump continued to heat the home with backup resistance heat. Diagnosis of this problem indicated a low charge of refrigerant that was corrected and the unit operated properly for two weeks when the same fault occurred again. The problem was finally determined to be a defective expansion valve that was replaced in February, 1995. Following replacement of this valve, unit 3 had no further mechanical problems throughout the test period. However, the residents of unit 3 operated the system in a manner which significantly impacted its energy consumption. The thermostat setting on unit 3 was frequently varied between 60 and 75 °F, as reflected by return air measurements shown below. Also, in the winter, the "emergency heat" switch on the thermostat was apparently selected which would start the resistance heaters. No doubt, the residents were not familiar with the operation of the system and they were not receptive to our attempts to meet with them. Since the instrumentation indicated the unit was functioning properly and supplying adequate space conditioning, we continued monitoring the system but have used data from unit 3 only with qualification.

Weather Conditions During the Test

Heating and cooling degree-days, based on hourly average temperature readings recorded at the test homes, are shown in Figure 7 for the period from February 1995 through August, 1996. Heating degree-days are accumulated when the hourly average outside air temperature is below 65 °F, and cooling degree-days accumulated for outside air temperatures above 70 °F

For a the one year period (from 2/95 through 1/96) there were 2280 heating and 1872 cooling degree-days accumulated. These data are consistent with 10 year average data collected at Ft. Hood [3] indicating 2300 heating and 2000 cooling degree-days. Maximum and minimum temperatures observed are also consistent with the 10 year records.

Return Air Temperatures

The return air temperature at the air handler/heat pump intake plenum is a measure of home interior temperature. Figures 8 and 9 show typical variations in the return air temperatures for the three GHP homes for both winter (February, 1995) and summer (June, 1996) conditions. Not surprisingly, all the test homes are maintained at different interior temperatures based on the tastes of the individual residents. Most of the homes are roughly comparable, however, with the exception of the unit 3 GHP which exhibited unusually large variations in interior temperature in both the winter and summer.

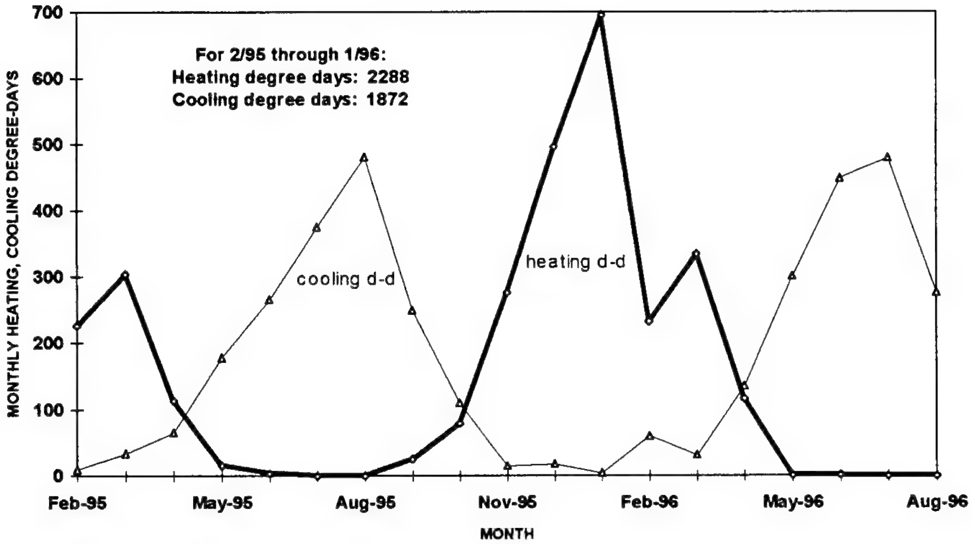

Figure 7. Measured heating and cooling degree days at the Ft. Hood site

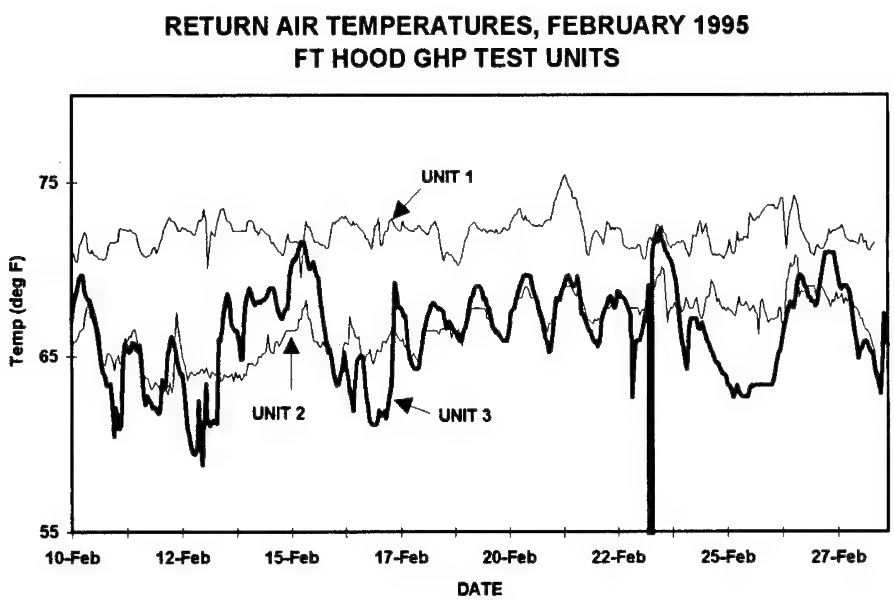

Figure 8. Winter return air temperature, GHP test units

There was no indication from the return air data that either the heat pumps or the conventional HVAC hardware could not maintain desired temperature levels in these homes for essentially all the weather conditions encountered during the test.

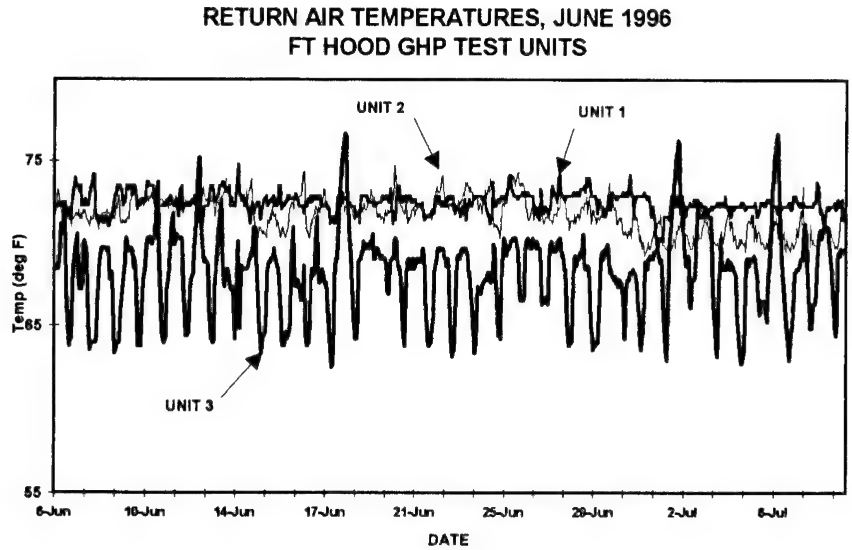

Figure 9. Summer return air temperature, GHP test units

Loop Temperatures

The loop temperature for a geothermal system is a fundamental parameter governing its efficiency and capacity. For a closed loop system, the local transient heating or cooling of the ground near the ground loop [1,2] produces seasonal variations in the loop temperature even though the undisturbed ground temperature remains constant. A properly designed closed loop system yields seasonal extremes which are within design goals.

To indicate this effect, Figure 10 shows maximum and minimum hourly average loop temperatures for units 1 and 2. In this figure, loop temperature is defined as the average entering and leaving loop temperature, in order to avoid any corrections for the different loop flow rates for these units. The differences in loop temperatures between units 1 and 2 are expected, because unit 1 has a larger heat pump yet both have the same installed loop length. The loop temperatures for unit 1 operate between 53 and 95 °F and unit 2 between 59 and 88 °F. These values are consistent with the design goals set for the GHP's.

A more detailed comparison with the theoretical predictions of loop temperature is given in Figure 11. In this figure, a scattergram for unit 1 is created with hourly average pairs of outside air temperature and loop temperature. The WFEA software assumes a simple relationship between outside air temperature (related to building thermal load) and loop temperature. The design software results, also shown on Figure 11, reasonably average the scatter points. Exact matching cannot be expected, of course, because the loop temperature at any given time depends on the building load and thermal load history of the loop. For example, with the same outside air temperature, loops run hotter at the end of the summer than

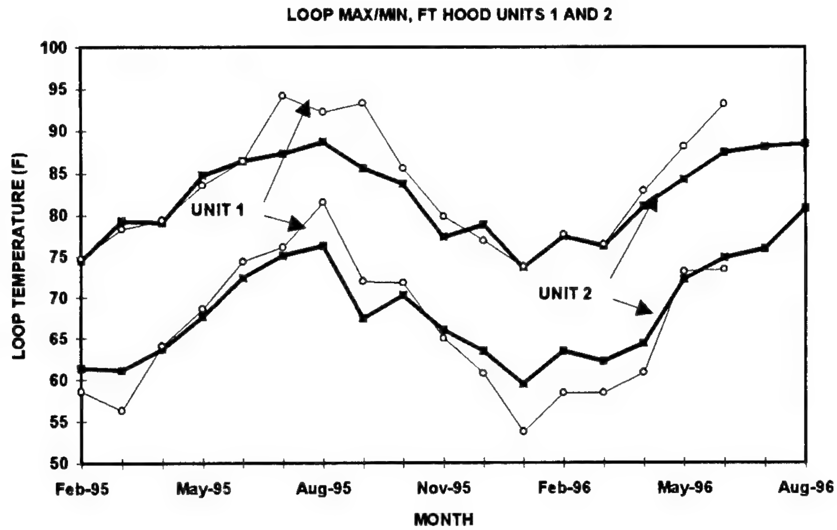

Figure 10. Loop temperature extremes (hourly averages)

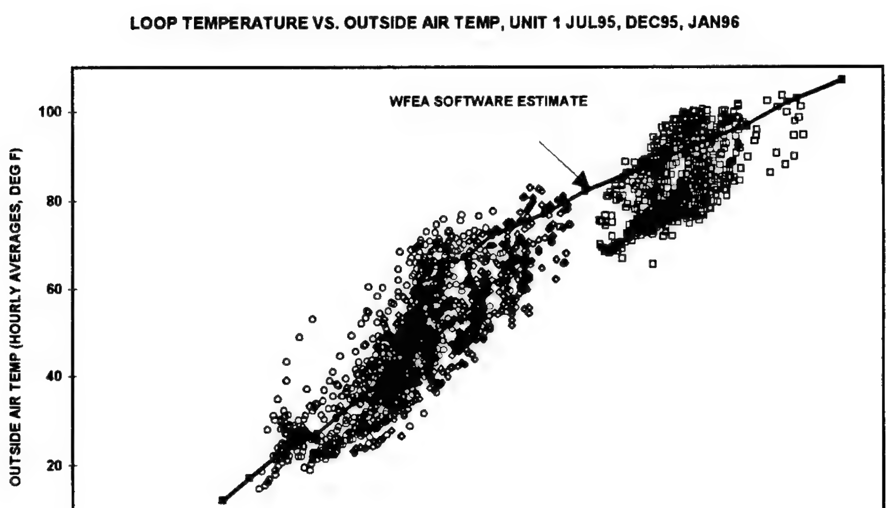

Figure 11. Measured loop temperatures compared to WFEA software prediction

at the beginning because of soil heating near the loop. Another notable difference between the analysis and this installation is the total bore length used for the analysis (660 ft) and this test unit (750 ft). Use of the as-built loop length in the analysis would reduce the maximum loop temperature by about 6 °F and raise the minimum by a similar amount. Considering the general uncertainty about actual system loads and the thermal conductivity of this site, the WaterFurnace loop design software has done a good job of matching the loop temperatures observed at this site.

HVAC Duty Cycle

The sizing of HVAC hardware affects the duty cycle. Oversized equipment produces a relatively low duty cycle and easily satisfies peak loads. However, such a choice increases installed cost, increases peak electrical demand, and in air conditioning mode, may not properly dehumidify living space. Undersized equipment has a higher duty cycle. With undersized equipment, peak loads are not satisfied and equipment lifetime may be reduced. Ideally, a properly sized system should approach 100% duty cycle under peak load conditions.

Figure 12 is a scattergram of hourly average duty cycle vs. hourly average outside air temperature for unit 1 operating over the months of July and December, 1995. Also shown is a prediction from the WFEA software. This prediction is based on the peak design calculations for heating and cooling loads. For these data, covering a range of outside air temperatures between 20 and 100 °F, the "average" duty cycle is well below 100 %, although there are individual points approaching 100 %. This indicates that the sizing of the heat pumps falls between "just right" and oversized.

Not shown on Figure 12 is the duty cycle for the auxiliary resistance heaters because measurements indicated essentially no demand for resistance heat on units 1 or 2 for the entire test period. As mentioned above, unit 3 had the unusual behavior of operating almost entirely on resistance heat through both heating seasons. We assume this is because the thermostat switch was set on "Emergency Heat" by the residents. Unfortunately, we were not able to confirm this directly with the residents or gain access to the heat pump unit, although our instruments indicated the unit 3 heat pump compressor was functioning properly. It is possible that an internal malfunction in the heat pump could yield the same result.

Figure 13 shows a similar scattergram for the unit 2 gas furnace and air conditioner. The conventional AC operates at near 100% duty cycle when the air temperature is above 90 °F. This indicates that the conventional AC equipment is somewhat undersized and falls short of removing the peak cooling load on this unit. The gas furnace, alternatively, has no problem following the heating load. This is expected because the heat output of this 75,000 Btu/hr input furnace greatly exceeds the calculated peak heating load.

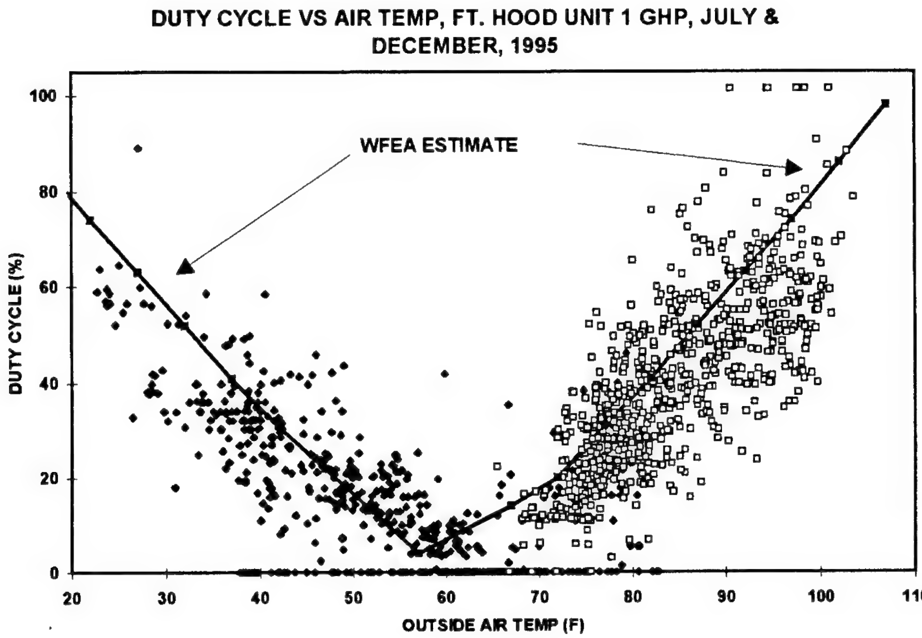

Figure 12. Hourly average duty cycle for unit 1 GHP. The solid points correspond to heating conditions, the open points for cooling.

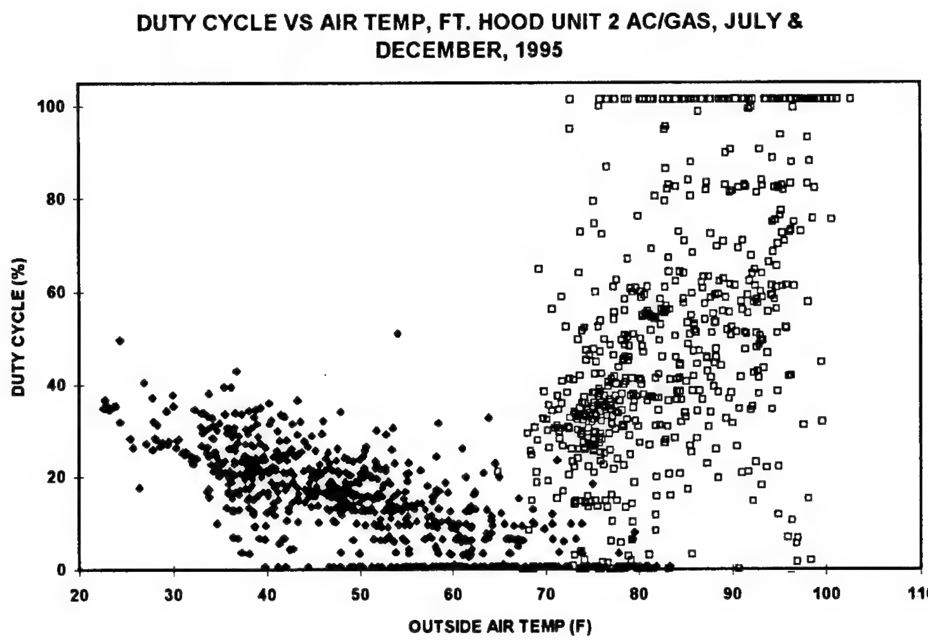

Figure 13. Hourly average duty cycle for unit 2 furnace and AC

Energy Use Characteristics

The monthly electrical energy consumption for the GHP and conventional HVAC systems is summarized in Figure 14. It is clear from these plots that with the exception of unit 3, the GHP systems offer considerable savings in energy use, particularly during heavy use months in the summer.

The high energy use of unit 3 has been previously discussed. The high use of resistance heat has a large, obvious impact on the winter heating energy use. The relatively high energy use of unit 3 in the summer is due to the low interior temperatures the residents prefer and the frequent thermostat changes made. In some cases, unit 3 actually operated in heating mode in the summer to follow changes evidently demanded by the thermostat.

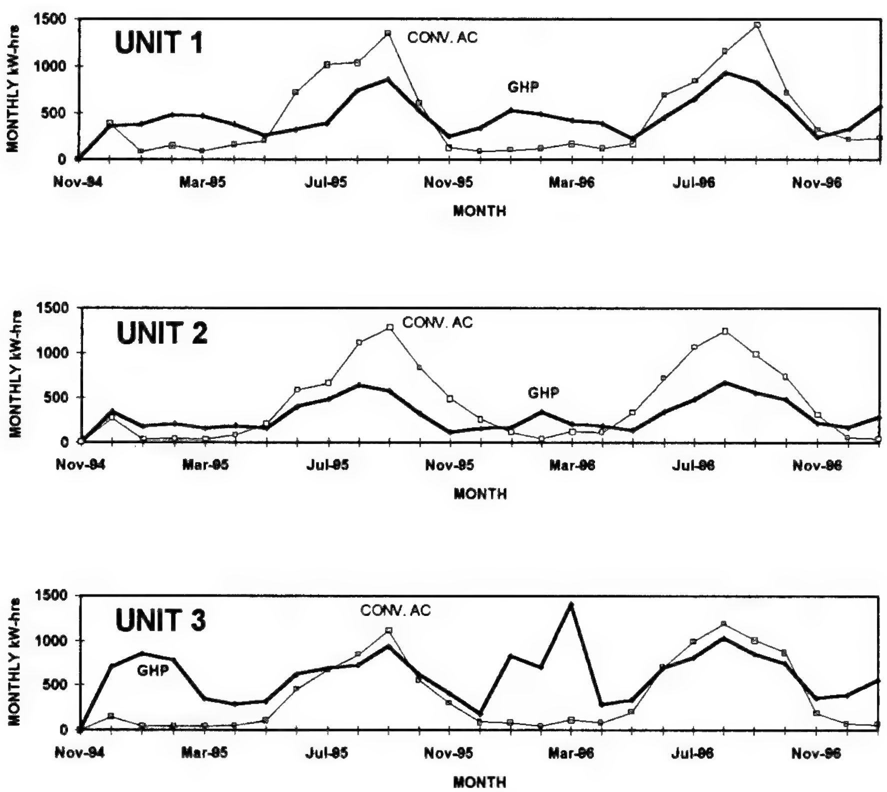

Figure 14. Monthly HVAC electrical energy use for GHP and conventional units at Ft. Hood. Conventional AC air handler energy not included in these figures.

It should be recalled that the savings situation is actually somewhat better than shown on these plots because the conventional AC meter does not include the air handler energy. We estimate the air handler energy is about 150 kW-hrs/month during peak summer months. This adjustment would yield an increase of measured AC electrical energy of about 10%. The adjustment in the winter to the gas furnace would be less, about 75 kW-hrs, because of the lower duty cycle of the gas furnace.

The energy use for the gas furnace was measured indirectly. From the run-time meters installed on the furnace gas valve, the average duty cycle of the furnace was recorded for 20 minute, hourly, and monthly intervals. The gas use was estimated from the nameplate input rating of the furnaces (75,000 Btu/hr or .75 therm/hr) and the measured furnace run time.

Table 2 shows seasonal energy performance of the test units, in terms of kW-hrs and gas therms consumed.

	UNIT 1			UNIT 2			UNIT 3		
	GHP	AC	GAS	GHP	AC	GAS	GHP	AC	GAS
WINTER '94-'95	2067	871	260	1075	465	347	2952	319	366
SUMMER '95	3355	5070	23	2701	5177	38	4296	4035	32
WINTER '95-'96	2173	606	443	1076	665	442	3407	413	361
SUMMER '96	3910	5344	13	2898	5393	14	4805	5146	9
TOTALS:	**11505**	**11891**	**738**	**7750**	**11700**	**841**	**15460**	**9913**	**767**

Table 2. Measured seasonal energy consumption of the Ft. Hood test units (GHP and AC in kW-hrs, gas furnace in therms)

These data may be converted to energy costs using the approximate base rates of $.055/kW-hr for electricity and $ .4/therm for gas. This estimate does not include demand charges for either utility. Table 3 gives results for such a calculation and further includes a correction to add the electrical costs needed to operate the 500W air handler fan for the gas/AC test units. This correction is calculated based on the measured run time of the air handler. Table 4 indicates the percentage savings offered by the GHP systems.

	UNIT 1			UNIT 2			UNIT 3		
	GHP	AC	GAS	GHP	AC	GAS	GHP	AC	GAS
WINTER '94-'95	$114	$48	$113	$59	$26	$152	$162	$18	$160
SUMMER '95	$185	$320	$10	$149	$334	$16	$236	$258	$14
WINTER '95-'96	$120	$33	$194	$59	$37	$193	$187	$23	$158
SUMMER '96	$215	$346	$6	$159	$349	$6	$264	$330	$4
TOTALS:	**$633**	**$748**	**$322**	**$426**	**$745**	**$367**	**$850**	**$628**	**$335**

Energy costs based on $.055/kW-hr for electricity, $.40/therm for gas.
Estimated energy use by gas furnace/AC air handler included

Table 3. Seasonal energy costs for the Ft. Hood test units

	UNIT 1	UNIT 2	UNIT 3
AVG. % WINTER SAVINGS:	40%	71%	2%
AVG. % SUMMER SAVINGS:	41%	56%	17%
AVG. % ANNUAL SAVINGS:	41%	62%	12%
AVG. ANNUAL HVAC $ SAVED:	$218	$343	$56

Table 4. Averaged HVAC savings for the Ft. Hood test units.

It is apparent from these results that with the exception of GHP unit 3, the Ft. Hood GHP systems offer impressive savings in seasonal and annual energy costs.

Another feature of the GHP systems is their ability to reduce peak demand. The demand at Ft. Hood peaks sharply in the summer (The base has a load factor of approx. 50 %, i.e. the peak summer load is double the annual average load) due to demand by facility air conditioners. This effect is shown in Figure 15, where the peak demand for the GHP is about 50% less than that for the conventional air conditioner.

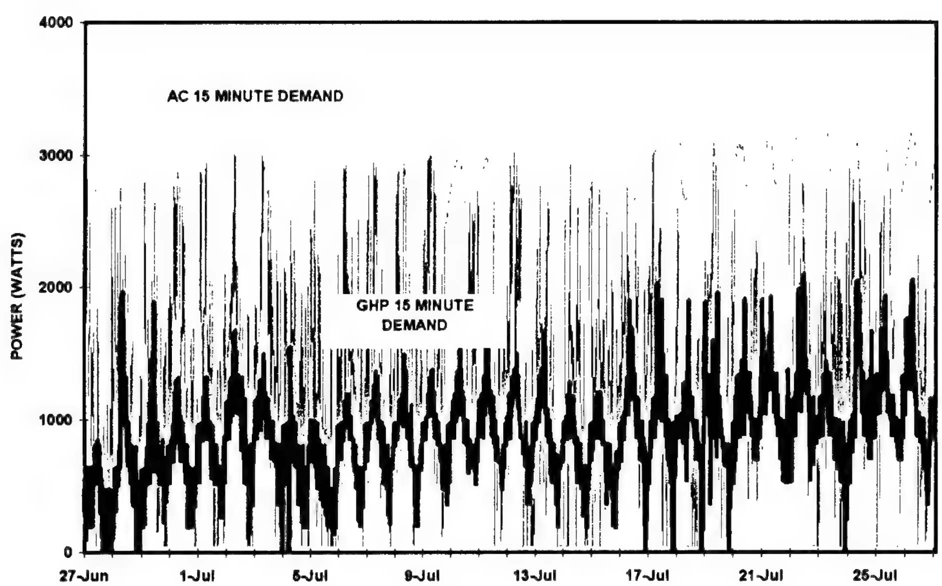

Figure 15. Demand reduction observed on unit 2, July 1995

Maintenance

There were no unscheduled repairs made to the GHP systems throughout the test period other than for the startup problems mentioned above. After about 6 months of operation, there was an automatic

shutdown of unit 1 caused by a very dirty air filter. When this occurred, all the GHP filters were changed and put on a regular schedule for filter changes.

Although the reliability of the GHP units tested was high, the duration of this test was far too short to draw any conclusions regarding the long-term maintenance costs of GHP systems. Because GHP construction and design is similar to conventional AC hardware, we would expect their long-term reliability to be similar to conventional systems.

Design Improvements

The test results show that the GHP systems performed essentially as designed and provided excellent space conditioning for all the test homes. Our review of the engineering data does indicate that the GHP design parameters were conservatively selected, as was the design intent.

The GHP installations would probably provide equivalent comfort at less cost with the following changes:

1. Use smaller heat pump units. The duty cycle data indicate that the units in this test easily satisfied peak loads. We believe that similar efficiency units with reduced capacity, by approximately 1/2 ton (6000 Btu/hr), would also be able to satisfy the loads. Smaller units would also further reduce peak demand.

2. Reduce loop length. This suggestion is based on the moderate max/min loop temperatures observed on this test. We would recommend only a modest reduction, however, from 750 to 700 ft. for the larger homes and 750 to 650 ft. for the smaller ones.

3. Use desuperheaters to provide domestic hot water.. As mentioned in the design section, this was not an option for the Montague homes under test due to the layout of the homes. It may be possible for other homes at Ft. Hood.

Changes 1 and 2 would, of course, reduce the performance margins that may now cover excessive losses due to construction flaws, duct leaks, poorly fitted windows and doors, poorly back filled loops, or unusual occupancy patterns.

GHP cost effectiveness at Ft. Hood

There are many complex economic, political, technical, and intangible factors, well beyond the scope of this report, which govern the decision of a military base to use GHP's or any other energy saving system. We will provide a simplified economic analysis based on cost estimates and performance measurements made from this demonstration.

The contract cost for the conversion of the three test homes to GHP's was approximately $10K/ per home, including a $500 GHP rebate provided by TU Electric to the contractor. This cost is much larger than one would expect in a larger scale conversion (say, 50 homes or more) because the contractors' design, mobilization, contingency and set up costs are a larger fraction of a small, three home project than for conversion of a subdivision. Our demonstration contracts also included some effort supporting the measurement program which would not be included for normal retrofits.

Because this demonstration indicated that drilling and in-house conversion of the homes in this subdivision is straightforward, we estimate that a large scale (50 units or more) conversion of homes in this subdivision to GHP's could be done for approximately $5K per home. This cost should be compared to the cost of replacing the current HVAC hardware which is nearly at the end of its useful life. Installing new 85% efficient furnaces and 10 EER central AC hardware is estimated to cost approximately $2600, included labor for removal and replacement of existing hardware. This yields an incremental first cost premium for the GHP of $ 2400.

The annual energy cost savings relative to the current installed hardware is taken from Table 4. Averaging units 1 and 2 savings yields an annual savings of $280/year. The new replacement conventional AC/furnace will certainly use less energy than the current 20 year old hardware. Assuming that new, conventional AC hardware would obtain half the savings observed with the GHP, the annual incremental energy savings from the GHP would be $140. Assuming no difference in maintenance costs for the GHP relative to the replacement conventional hardware, the simple payback period (i.e. payback without interest on the initial capital and without energy cost inflation) for the GHP system is 17 years.

This is a long simple payback and is due mainly to the very low annual energy costs relative to the cost of GHP systems. Better accounting of the savings due to reductions in demand charges, future escalation of energy rates relative to the cost of capital, and utility or government incentives could significantly reduce the payback period. There are also supportable claims that maintenance costs for GHP hardware are less than for conventional gas/AC systems [5].

Selfridge Demonstration

Site Characteristics

The Selfridge demonstration site is on the Sebille Manor subdivision of family housing units associated with the Selfridge Air National Guard (SANG) base. SANG is a large military facility located approximately 25 miles NE of the Detroit metropolitan area on the shores of Lake St. Claire and near the town of Mt. Clements, MI. Although SANG's name is associated with the air national guard, SANG is a multi-service base with Army, Navy, and Air Force functions resident there. The Sebille Manor subdivision consists of hundreds of military duplexes built in the 60's which are quite similar to the units at Ft. Hood. Sebille Manor is located a few miles north of the SANG boundaries on separate property owned by the base.

This site is characterized by cold winters and moderate summers. Military weather data [3] indicates a climate with 7000 heating degree-days and only 400 cooling degree-days. Winter design temperature is usually taken as 0 °F and the summer peaks based on 90 °F.

The Sebille Manor subdivision duplexes are "all electric" units (Figure 16). They are heated with baseboard resistance heat and do not have central air conditioning. Central air conditioning is not commonly used in residential housing in this area, although some residents use window units in bedrooms to deal with the few hot and humid days which occur every summer. The baseboard resistance heat is controlled by separate thermostats in each room. Domestic hot water is supplied by resistance hot water heaters located in the front hall closet. Other than the provision for hot water heaters, there are no utility cabinets or closets within the living space of the Selfridge homes.

Figure 16. Typical duplex residence, Sebille manor subdivision

The homes have attached single car garages which appear to have been converted from carports at one time. Most of the homes are ranch style with a simple, rectilinear floor plan under a simple pitched roof with a single ridge. Some of the units are L-shaped, however, with the garage roof ridge set a right

angles to the main roof. We mention this because the heat pump retrofit evaluated would be much more difficult to implement in the L-shaped homes.

The family housing units vary in size from about 1000 to 1300 square feet and have 2, 3, or 4 bedrooms. As with the Ft. Hood units, the homes are well maintained and have benefited from some upgrades in thermal insulation. Most of the homes had new looking siding laid over a 2 inch (approx.) layer of styrofoam or other insulating material. The attics are insulated with 3.5 inch thick fiberglass mats plus several additional inches of blown insulation.

The three homes selected for conversion to GHP's were chosen because they were empty during the construction period. This was done because the installation contractors estimated that a week or more would be needed for the conversion and that there would be substantial noise and dirt generated within the homes. The occupancy in Sebille Manor is essentially 100 %, but there is enough turnover to easily identify three homes that were empty between residents.

The most notable difference between test units is that unit 3 is a four bedroom 1-3/4 bath unit while units 1 and 2 have three bedrooms with 1 bath.

The local terrain is very flat. A local loop installer had drilled frequently in this vicinity, primarily with a hollow stem auger. The driller predicted that the soil at the test homes would be saturated clay and that his hollow stem auger would be able to drill from 120 to 180 ft before frictional effects stall the auger.

System Design

The heat pump systems were jointly designed by Rich Lavack of R&L Heating and Cooling and Rob Derkson of Water Furnace International. Both are experienced with GHP systems and have designed and installed many units in the Detroit area.

A key feature of this conversion was a ductwork concept conceived by Rich Lavack. Although there is very limited attic space, there was enough space to lay a backbone supply and return duct along the length of the home underneath the roof ridge line. A horizontal heat pump hung from the ceiling in the garage would be attached to these backbones. Lateral 4" round flexible supply ducts were attached between the rigid supply backbone and ceiling mounted registers located as close to the exterior wall as space would allow. Return air was collected through floor level registers set on interior walls. and passed upward between studs in the walls (no ducts) and collected into the attic return air backbone. Review of the floor plans indicated this concept could provide a good return air system with a return air register in every room of the homes.

A problem with this approach was the possibility of firestops (horizontal framing) in the interior walls. This turned out to be true, and there was added labor needed to locate and remove the horizontal framing. Another problem is that a small percentage of the homes in the subdivision have garage roof ridges at right angles to the main home roof ridge. These homes would require significantly more complicated ductwork to connect the home to a garage located heat pump.

The use of desuperheaters for domestic hot water was considered and rejected for two reasons. As was the case with the Ft. Hood tests, the hot water heater was not located near the heat pump and plumbing the desuperheater would require attic piping, a very undesirable idea in this cold climate. Secondly, in this heating-dominated climate, using desuperheaters for domestic hot water reduces the effective capacity of the heat pump system for space heating. Because most cold climate heat pump designs use supplemental heat because they are undersized relative to peak heating loads, desuperheating reduces the available capacity that must be replaced with more supplemental resistance heat. Increasing the size and capacity of the heat pump can counter this effect, but this will increase first costs considerably.

The peak heating load for the largest of the three homes was calculated with Manual J [4] to be 47,000 Btu/hr at the design winter temperature of 0 °F. The smallest test home had calculated losses of 42,000 Btu/hr. Cooling loads were calculated to range from 26,000 to 21,000 Btu/hr at a 90 °F design condition.

A heat pump unit designed for the largest home was assumed to be acceptable for the smaller ones. The designers selected a WaterFurnace SX 036. This unit has good efficiency (ARI 330 cooling EER of 13.6 and heating COP of 3.2), though not as good as the AT units used at Ft. Hood.

The loop design assumed fully saturated soil with a conductivity of 1.4 Btu/hr-ft-°F. This is a relatively high conductivity compared to less saturated soil conditions [1]. The resulting simulation of performance is summarized in Table 5. The designers choose a total bore depth of 435 ft which yielded a minimum design winter loop temperature of 30 °F. Note that with this design, when the outside air temperature is 17 °F or less, the heat pump alone cannot supply the energy demanded by the building. Because of this, 5kW strip heaters were added to the heat pump plenum. These heaters, along with the heat pump compressor, should easily meet the peak load condition at this site.

It would be possible, of course, to select a larger heat pump which would reduce or eliminate the need for resistance strip heat. The experience of these designers indicated that the added expenses for additional loop length, and the cost of a larger heat pump unit would not be justified by the minor savings obtained. The current design, incidentally, indicates that only 6 % of the total annual heating electrical energy consumed would be used by the resistance heaters.

Because the Selfridge homes have larger thermal loads, the shorter loop length for the Selfridge design (435 ft) relative to the Ft. Hood design (750 ft) appears paradoxical. There are several factors, however, that explain this difference. First, the soil conductivity at Selfridge, due to the water saturation, is larger. Second, Selfridge is a heating-dominated design and so the loop need only supply building loads less compressor work. This puts much less thermal load on the loop than is the case for a cooling dominated (i.e. Ft. Hood) site. Finally, the Selfridge design does not satisfy the peak heating load with the heat pump. This effectively reduces the thermal loading on the ground loops.

A design review was held at Selfridge in February 1995. A number of changes were made to the design following this review. The original design had a loop minimum temperature of 25 °F which required a loop length of 340 ft. Sandia requested that the design minimum temperature be raised to 30 °F to

WEATHER		GHP SYSTEM			
AIR TEMP °F	ANN. HOURS	EST. LOOP TEMP, °F°°	GHP OUTPUT (Btu/hr)	EST. LOAD (Btu/hr)	GHP DUTY CYCLE (%)
112	0				
107	0				
102	0				
97	9	94	33,906	29,777	88
92	47	85	35,460	24,970	70
87	148	77	36,951	20,163	55
82	314	69	38,387	15,356	40
77	516	61	39,776	10549	27
72	721				0
67	783				0
62	695				0
57	633	52	-36,663	-111	0
52	592	49	-35,200	-3,471	10
47	566	46	-33,749	-6,831	20
42	595	43	-32,311	-10,191	32
37	808	40	-30,887	-13,552	44
32	884	37	-29,476	-16,912	57
27	618	35	-28,082	-20,272	72
22	377	32	-26,703	-23,632	89
17	248	30	-25,808	-26,992	100
12	131	30	-25,808	-30,353	100
7	61	30	-25,808	-33,713	100
2	17	30	-25,808	-37,073	100
-3	4	30	-25,808	-40,433	100
-8	1	30	-25,808	-43,793	100

Table 5 Predicted performance for the Selfridge homes

increase the conservatism and energy savings potential of the design. There was discussion about limiting thermal losses in the ductwork, most of which would be installed outside the insulated building envelope. It was concluded that a best effort would be made to insulate the ducts as well as possible within the severe space limitations of the attic. It was also decided to add some instrumentation to the ductwork to get data on the losses which actually occur.

Installation

Construction began in early May, 1995. The first phase consisted of installing the heat pumps and ductwork. Most of the ductwork was pre-fabricated at the HVAC contractor's shop prior to arrival on site. There were some field changes needed as the homes finally selected had slightly different floor plans than the drawings used by the HVAC contractor.

Installation of the attic supply and return ducts proved to be difficult but possible. The ceiling mounted supply registers were installed about 5 ft from the exterior walls. Horizontal blocking was found in the interior walls which had to be removed to allow return air to flow up between studs in the interior walls. This caused considerable damage to the interior sheetrock which had to be repaired. The SX 036 heat

pumps were suspended from rafters in the garage and connected directly to the main supply and return ducts

The installation turned out to be tedious, taking a two to three man crew close to three working days to complete each home. In spite of the difficulties, the final installation looked professional and transparent to the residents. Figures 17 and 18 show views of the home interiors after the heat pump installation.

Loop installation proved to be a major problem. Drilling was delayed until late May because of unseasonably cold weather. The driller initially brought a lightweight (under 25,000 lbs) hollow stem auger to the site and expected to be able to drill 120-180 ft bores with this rig. It was discovered right away that a hard shale layer at 25 to 35 ft below the surface could not be penetrated by the auger. This layer was present at all the test sites in the subdivision, so no bores were completed with the auger. The driller had just ordered a much larger 50,000 lb mud rotary and auger rig that was expected to arrive in a few weeks. It was decided delay the drilling and wait for the larger rig.

The mud rotary drill was able to penetrate the rock layer, but not without several days and a variety of bits spent before finding an effective combination of bit, mud and rig parameters. Cleanliness with the drilling operation proved to be a problem as the heavy rig sank through the landscaping, leaving deep ruts and drilling mud returned through previously abandoned bores (Figure 19). Although the rig was eventually configured to drill readily to 250 ft, the clay in the geology was unstable and keeping the bores open long enough for loop insertion was a problem. Indeed, the longest loop actually inserted on the site was 150 ft. Units 1 and 2 as-built loops each consisted of three 150 ft. bores. Because of loop insertion difficulties, unit 3 actually had four loops with bore lengths of 80, 100, 80, and 120 ft., respectively. The shortage of total borelength on unit 3 was made up with additional header length in surface trenches. When the drilling was finally completed at the end of June, the yards of all the homes needed major repairs to the landscaping. Fortunately, the homes have simple landscaping and simple leveling, re-sodding and small shrub replacement restored the site (Figure 20).

The heat pump installation was completed in July with installation of the loop pumps and air purging and filling the loops with aqueous methanol antifreeze solution. The units were turned on and appeared to be functioning normally.

Instrumentation and Data Acquisition

Data acquisition for this project was handled by UTS Systems, a subsidiary of Detroit Edison. Bob Pratt of UTS was the lead engineer designing the data acquisition system. The initial contract was awarded in late September, 1995 and the acquisition hardware was installed and operational on all the test homes by December 1, 1995.

The goals of the measurement program were the same as for Ft. Hood but the approach was quite different. UTS decided to use a single programmable, multi-purpose logger in each duplex and configure the systems for downloading by telephone modem. UTS selected very accurate platinum resistance.

Figure 17. Heat pump unit suspended from garage ceiling.

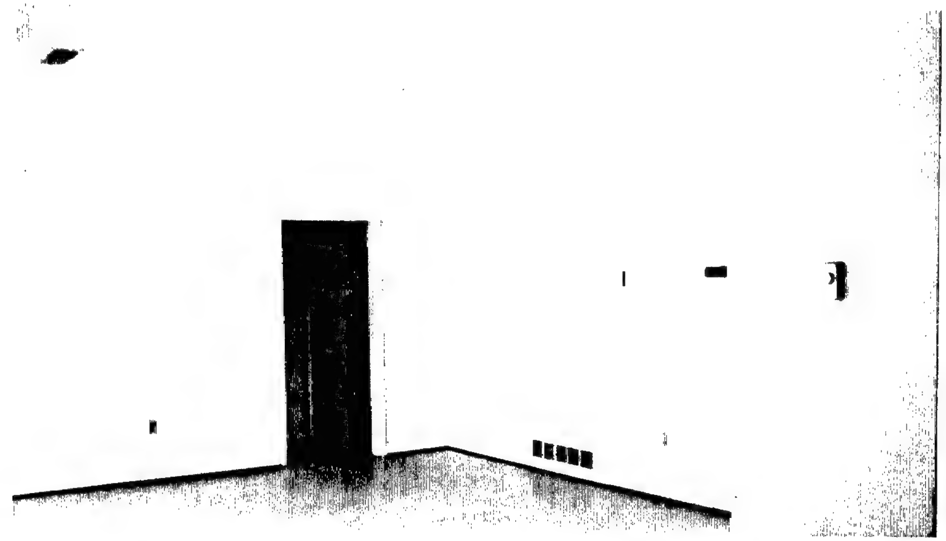

Figure 18. Living room after sheetrock repair and duct installation.

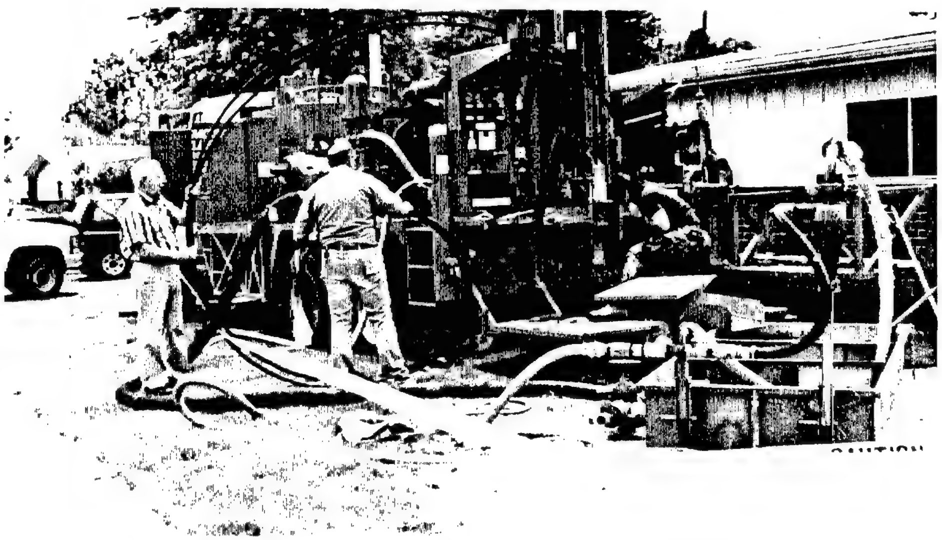

Figure 19. Mud rotary drilling rig operating in front yard.

Figure 20. Landscaping after repairs from drilling damage.

thermometers (PRT's) for all thermal measurements. The programmable logger used was a Synergistics Model C140E. This device was choosen because of UTS's familiarity and confidence with the unit and because it may be equipped with power transducer cards with split core current transformers

All of the channels recorded were stored as 15 minute averages. Each duplex recorded 18 channels, summarized in the following table:

MEASURED ITEM	QUANTITY/SENSOR
Geothermal Side	
Whole House Energy Use	kW-hr, split core current transformer
Heat Pump Energy Use	kW-hr, split core current transformer
Domestic Hot Water Energy Use	kW-hr, split core current transformer
Loop Temperature Entering Heat Pump (EWT)	°F, PRT
Loop Temperature Leaving Heat Pump (LWT)	°F, PRT
Return air temperature at heat pump plenum	°F, PRT
Supply air temperature at heat pump plenum	°F, PRT
Supply air temperature at most distant register	°F, PRT
Air temperature in attic	°F, PRT
Indoor temperature at thermostat	°F, PRT
GHP compressor run time	on/off clock, current sensor
Aux. Strip heat run time	on/off clock, current sensor
Conventional Side	
Whole House Energy Use	kW-hr, split core current transformer
Resistance Heat Energy Use.	kW-hr, split core current transformer
Domestic Hot Water Energy Use	kW-hr, split core current transformer
Outdoor Air Temperature	°F, PRT

Table 6. Data acquisition channels for each Selfridge duplex

The data logger was placed in the garage in a semi-weatherproof locked box. The box is located near the home circuit breaker panels and all the current transformers for energy measurements are located inside the main breaker panel. Instrument lines to the logger were routed through the attic or otherwise hidden from the residents. The only damage to instrument wiring during the two year test period was caused by a puppy who chewed through the line to the outside air temperature sensor in the back yard of unit # 1.

A separate telephone line dedicated to communicating with the loggers was installed at each duplex and connected to an optional modem in the logger. This modem can be used to download stored instrument readings, monitor current instrument readings, and even reprogram the logger. The modem approach was suggested by UTS because of their distant (45 min drive) location from the test site. The modem proved to be a valuable asset for maintaining the quality and continuity of the site data because it facilitated frequent downloading so that failures in the system could be identified before losing too much data.

Following initial checkout of the system, the normal procedure was to download all channels of data on weekly basis. These weekly downloads were then combined into monthly Excel spreadsheets for archival. The quality and reliability of the data obtained was very high, with negligible loss of data throughout the two year test period.

The cost of the data acquisition hardware was approximately $5,000 per house , including all the sensors, wiring, and logging equipment. This is more than twice the installed cost of the SmartReader thermistor system used at Ft. Hood. There was, however, a major reduction in labor costs associated with downloading and archiving the data at Selfridge which more than offset the higher initial costs of the acquisition equipment.

Testing Results

Startup Problems

The heat pump units were started in July 1995 and data acquisition commenced in December. The only problem with the heat pump systems throughout the test period involved our failure to schedule regular changes of the duct filters. These filters became severely restricted by May, 1996 which led to very high supply plenum temperatures. This condition finally produced a compressor pressure fault in the unit 1 GHP. Replacing the filters in all the units improved the flow and all systems performed well afterwards.

Weather Conditions During the Test

Heating and cooling degree-days, based on the 15 minute average outside air temperature readings at unit 1, for most of the test period are shown in Figure 21. Note that the measured heating and cooling degree-days are quite consistent with the 7000 heating and 400 cooling degree days expected for this site based on 10 year site data [3].

Basic Performance of the GHP Hardware.

Because of the large differences in heating and cooling loads at this site, the performance questions are usually about the behavior of the GHP units in the heating mode. It is during the heating season that the heat pump is most fully loaded and may or may not provide comfort.

From the degree-days shown in Figure 21, it is apparent that one of the coldest months during the entire test period was January, 1995. Figure 22 and 23 indicates the behavior of unit 1 during that month. Figure 22 shows that the interior temperature (measured on the wall at the thermostat location) was maintained at about 75 °F throughout the month, which included low outside air temperatures approaching 0 °F. The instruments indicated, however, that in order to maintain comfort when outside

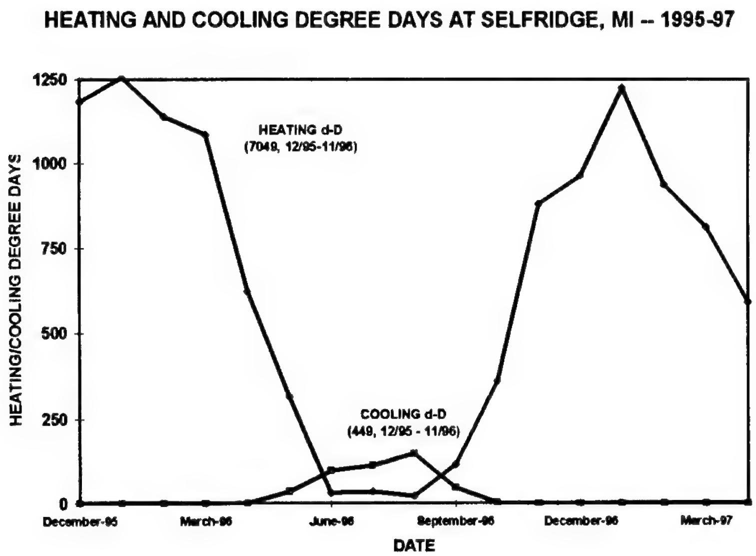

Figure 21. Measured 15 minute average heating (65 °F) and cooling (70 °F) degree days

air temperatures were low, a 5kW auxiliary strip heater was frequently used. This is consistent with the predictions of Table 5 which indicates that resistance heat will be needed when outside air temperatures fall below 17 °F. The auxiliary strip heat was rarely operated at 100% duty cycle, even under the coldest conditions, which would indicate that the heat pump with its auxiliary heater is adequately sized to carry the load.

Not shown in Figure 22 for clarity is the compressor duty cycle, but the measurements indicated that the compressor operated for approximately 80% of the time during this month and during cold periods the compressor would operate continuously for days at a time. This is, of course, exactly what the systems were designed to do. This is not the normal mode of operation for a residential forced air heating system and this led one resident to complain to us that the system "runs constantly" although they acknowledged that the home was comfortable during cold weather.

The supply and return air temperatures at the heat pump are indicated in Figure 23 for the same period. More detailed analysis of the data shows that during a cold month like this, the heat pump operating without auxiliary strip heat would yield supply air in the range of 100-105 °F. With the added heat from the strip heaters, plenum temperatures rise to the 110-115 °F range. It is apparent from Figure 23 that there is a trend toward rising supply air temperatures as the month proceeds. This trend is simply due to loss of air handler flow from the progressive clogging of the air filter and continued through May 1996 when the filters were belatedly changed. Changing the filter restored the supply temperatures to the 100-105 °F range.

PERFORMANCE OF SELFRIDGE UNIT 1 GHP, JANUARY, 1996

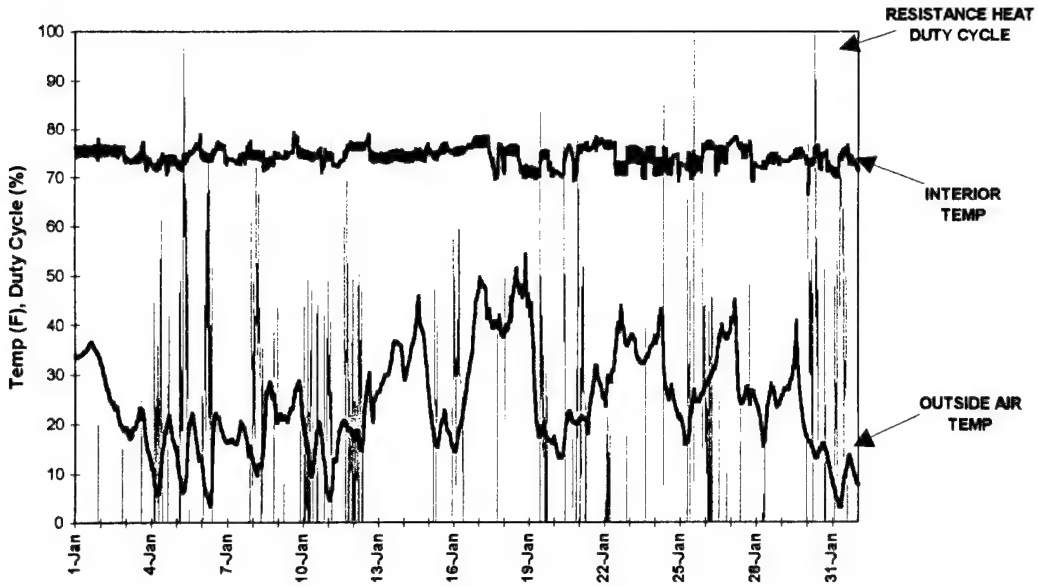

Figure 22. Unit 1 performance, showing strip heat duty cycle, outside air temperature, and interior room temperature.

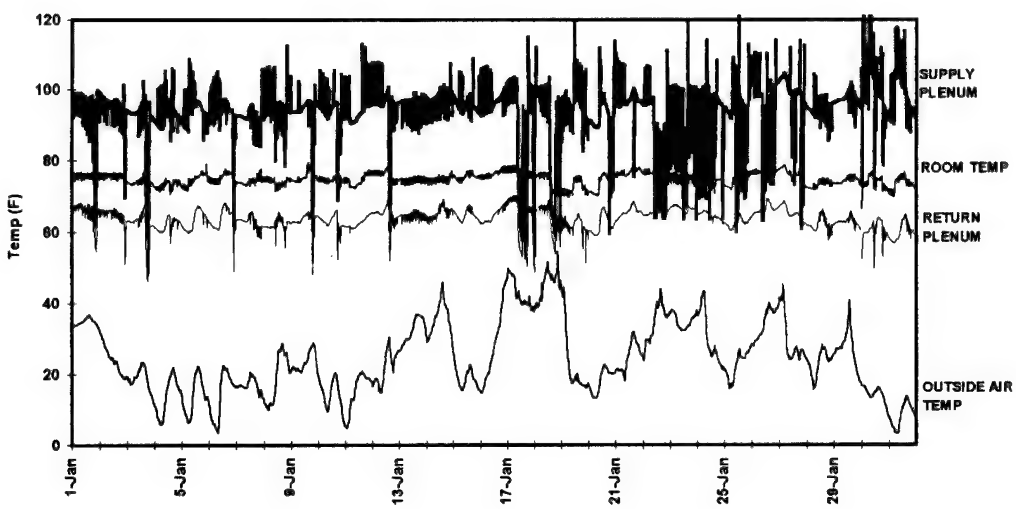

Figure 23. Supply and Return plenum temperatures for unit 1, Selfridge, MI, January, 1996

One other observation from Figure 23 is the approximately 10 °F reduction in temperature between the room air temperature at the thermostat and the return air plenum temperature. Part of this reduction may be explained by the normal floor-to-ceiling thermal gradient, and the fact that the return air registers are at floor level. We suspected, however, that duct losses were the major cause. A more detailed look at duct losses is summarized in Figure 24, covering a cold two day period in February 1996 when the outside air temperature ranged from -5 to 15 °F.

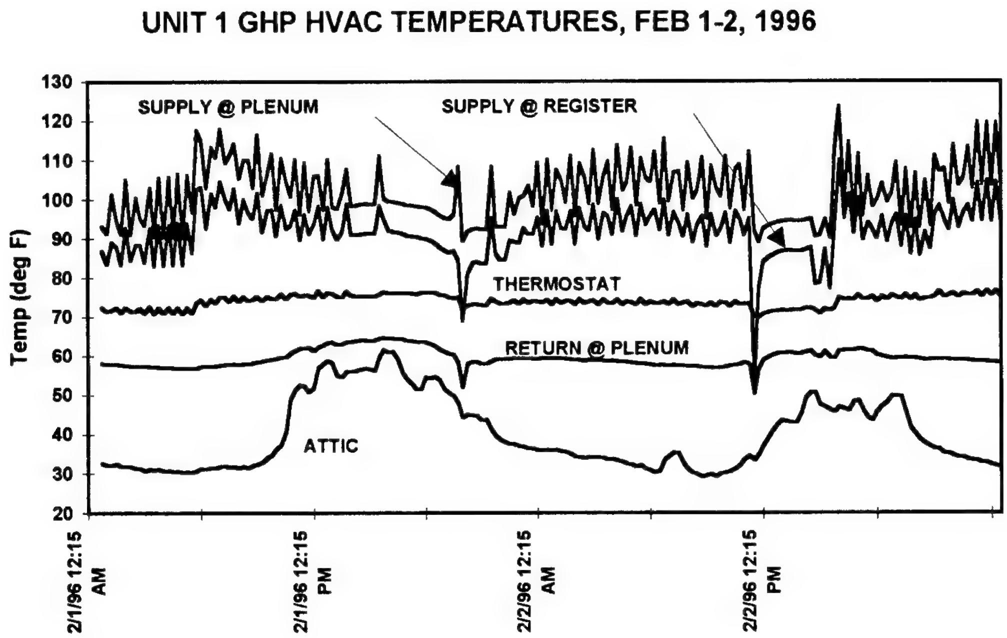

Figure 24. Temperatures in various parts of the duct system in unit 1 with outside air temperatures from -5 to 15 °F.

Figure 24 shows air temperature data in the supply plenum, at a bedroom ceiling mounted supply register, at the wall mounted thermostat, in the return air plenum, and in the attic space near the garage. The temperature drops in the ducts suggest that there is substantial loss of energy through this duct system. Both the supply and return duct systems are losing the order of 10 °F in air temperature across their length. Because the total difference in air temperature supplied by the heat pump and resistance heaters is about 50 °F, the duct loss observed in this figure is the order of 20% of the GHP energy supplied to the home. This estimate is an upper bound on the loss, of course, because outside air temperatures are not normally this cold.

The measured monthly average duty cycles for the compressor and resistance heaters are summarized in Figure 25 for all three GHP test units. As was mentioned above, the GHP compressors work hard during the peak load winter months, with monthly average duty cycles well above 80%.

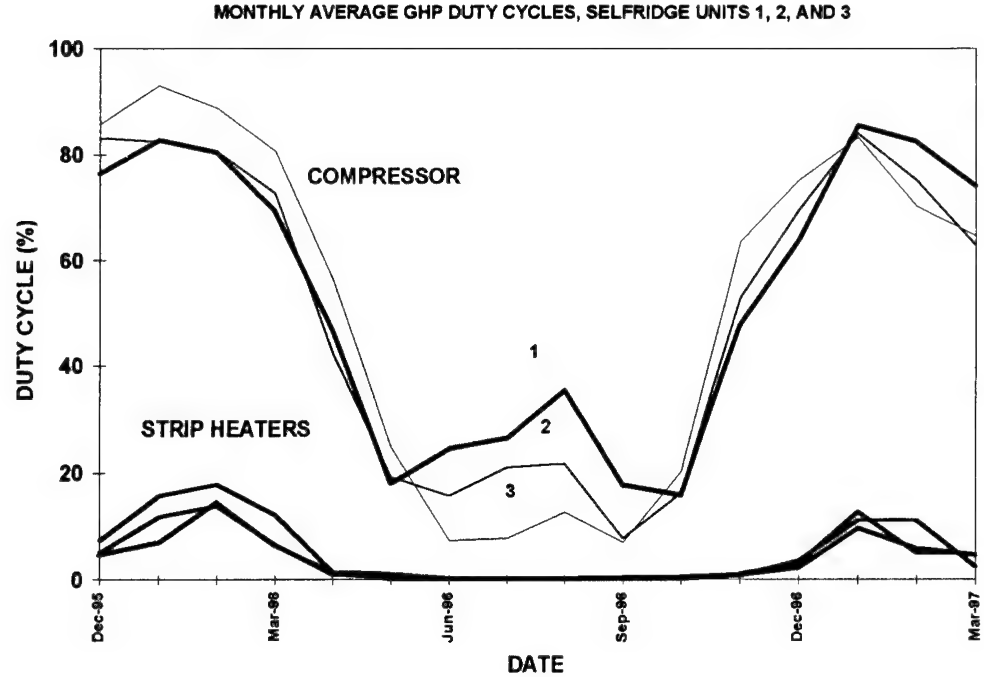

Figure 25. Monthly average duty cycles for the GHP compressors and resistance heaters.

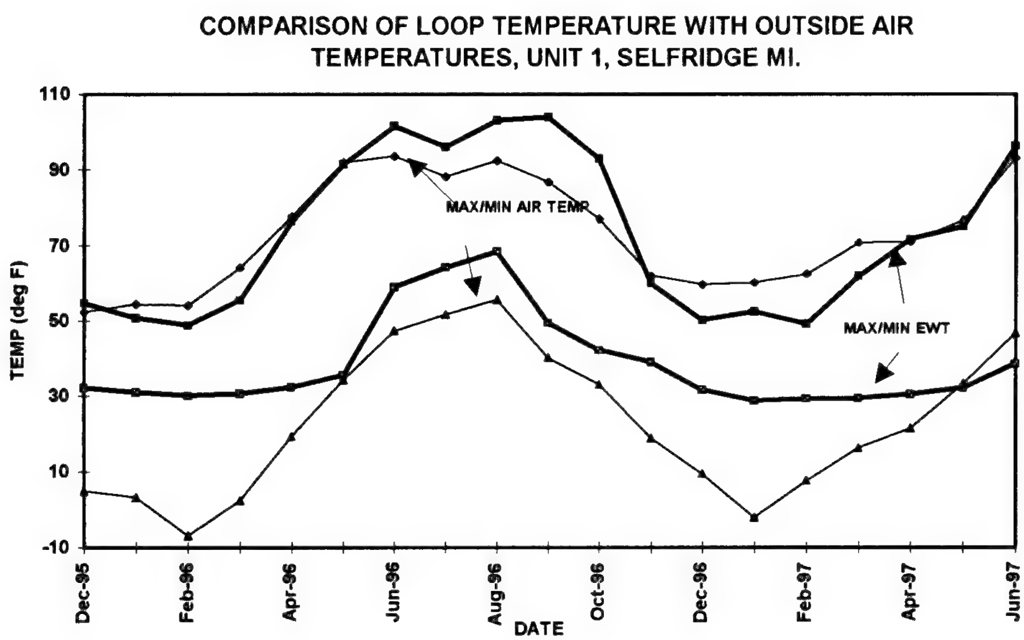

Figure 26. Loop temperature extremes measured for the test period

Loop Temperatures.

Figure 26 summarizes the loop entering water temperature extremes measured on unit 1 during the test period (units 2 and 3 exhibited similar behavior). The variations in loop temperature from summer to winter are much larger with the Selfridge homes than the Ft. Hood units because of the relatively shorter loops at Selfridge. This effect is pronounced during the summer cooling season when the Selfridge loops peak out at temperatures above 100 °F. However, because of the limited cooling load at Selfridge, high summertime loop temperatures have negligible effect on overall energy use.

The minimum loop temperature during the winter appears to exhibit a floor at around 30 °F. We believe this is caused by local freezing of the ground water near the loops and the leveling of net thermal load into the ground because of the increasing use of resistance heat as outside temperatures fall.. The improved thermal conductivity of ice and the large latent heat needed to freeze ice would strongly increase the net heat transfer per unit length of ground loop. This floor in loop temperature is even more obvious in Figure 27, a scattergram of 15 minute average loop temperatures vs. outside air temperature.

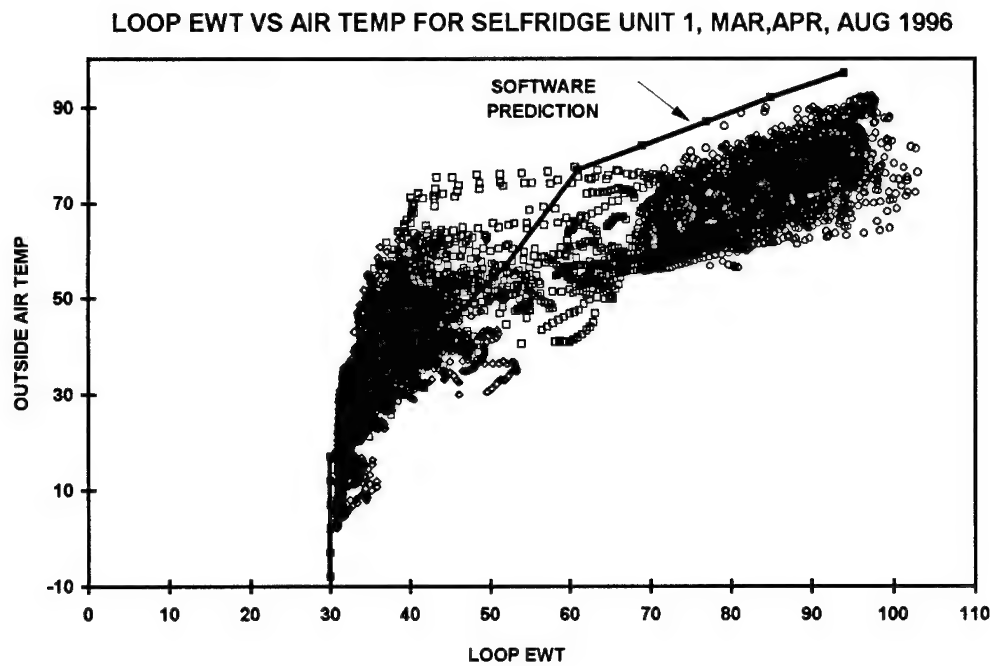

Figure 27. Loop temperature and outside air temperature scattergram.

This scattergram, also includes the predicted loop temperature given in Table 5. It is apparent from this plot that the summertime loop temperatures are higher than expected and winter temperatures lower, at least until the floor at 30 °F is reached. This lack of agreement is probably due to an overly optimistic estimated thermal conductivity for this site. In this particular case, the mis-estimate does not have a large

effect on system performance because most of the energy consumed by these heat pumps occurs when the loop temperature is on the 30 °F floor in mid-winter.

Energy Use Characteristics

The monthly energy use characteristics for the GHP units is compared with the energy use for the baseboard resistance heaters is shown in Figure 28. In this figure, the energy use includes only the GHP and the baseboard heating units and the energy use is averaged over the three test duplexes. It is apparent that the GHP's offer substantial savings in winter heating costs and provide summer cooling for modest additional cost.

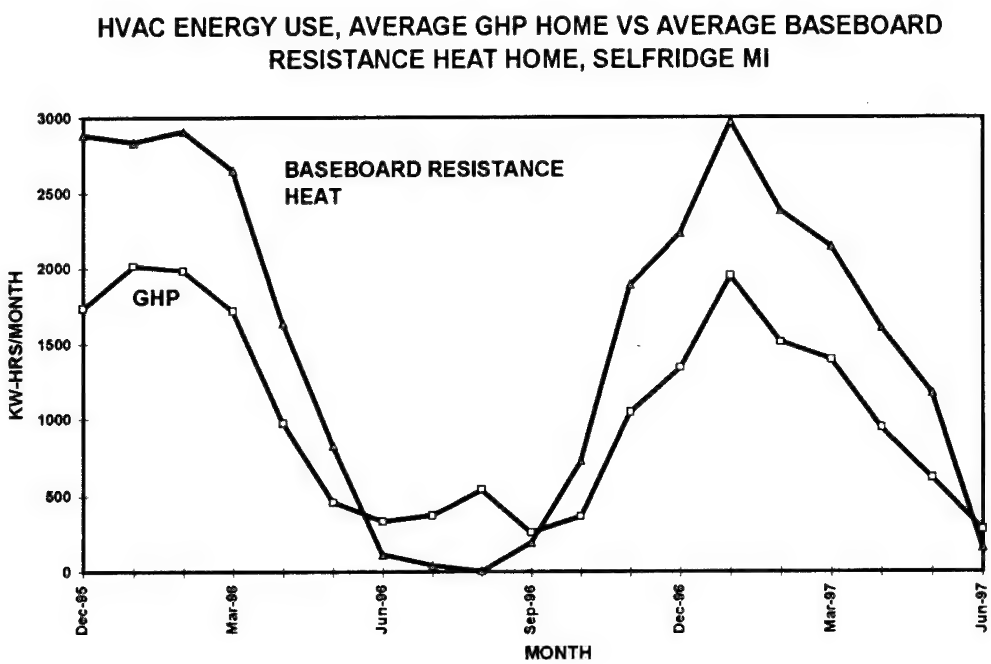

Figure 28. Monthly energy consumption for the test homes.

The actual savings measured over both winters and one summer of the test period are given in Table 7

	UNIT 1			UNIT 2			UNIT 3		
	GHP	CONV.	% SAVED	GHP	CONV	% SAVED	GHP	CONV.	% SAVED
WINTER '95-'96 (12/95-4/96)	$438	$630	30 %	$437	$761	43 %	$512	$738	31 %
SUMMER '96 (5/96-10/96)	$182	$86	-112 %	$114	$119	4 %	$86	$109	21 %
WINTER '96-'97 (11/96-4/97)	$451	$683	34 %	$433	$764	43 %	$464	$733	37 %

Table 7

These data indicate winter energy savings between 30 and 45% may be obtained with the GHP units. The additional costs for energy in the summer are not very significant relative to the total annual energy consumed and the GHP's provide the additional comfort of air conditioning.

While the savings in the winter are impressive, it was actually expected that the GHP savings for heating would approach 60 % or more relative to baseboard resistance heat.. This is because the GHP coefficient of performance (COP) is nearly 3.5 for the 30 °F loop conditions experienced at Selfridge. A 3.5 COP suggests that the GHP would provide 3.5 times more thermal energy than a resistance heater with the same energy input. There are several factors which probably contribute to the lower than expected savings observed.

One factor is the substantial use of auxiliary resistance heaters within the heat pump. These heaters supply additional energy needed at a COP of 1 and thereby reduce the effective system COP. Detailed review of the winter performance data indicate that approximately 15 % of the total energy consumed by the GHP's in the heating mode went towards powering the auxiliary strip heaters. If a larger GHP operating at COP of 3.5 were installed so that strip heaters were not needed, the energy use would be reduced by about 11%. This is not recommended, of course, without considering the additional costs of a larger heat pump and the loop field needed to support it.

Another issue concerns the duct losses that were observed in this installation. The duct losses approach 20% under very cold conditions and losses under these conditions will almost certainly be supplied by resistance strip heat since the capacity of the heat pump is limited. It is conceivable that if the duct losses were reduced significantly on these installations, the demand for auxiliary strip heat would approach zero.

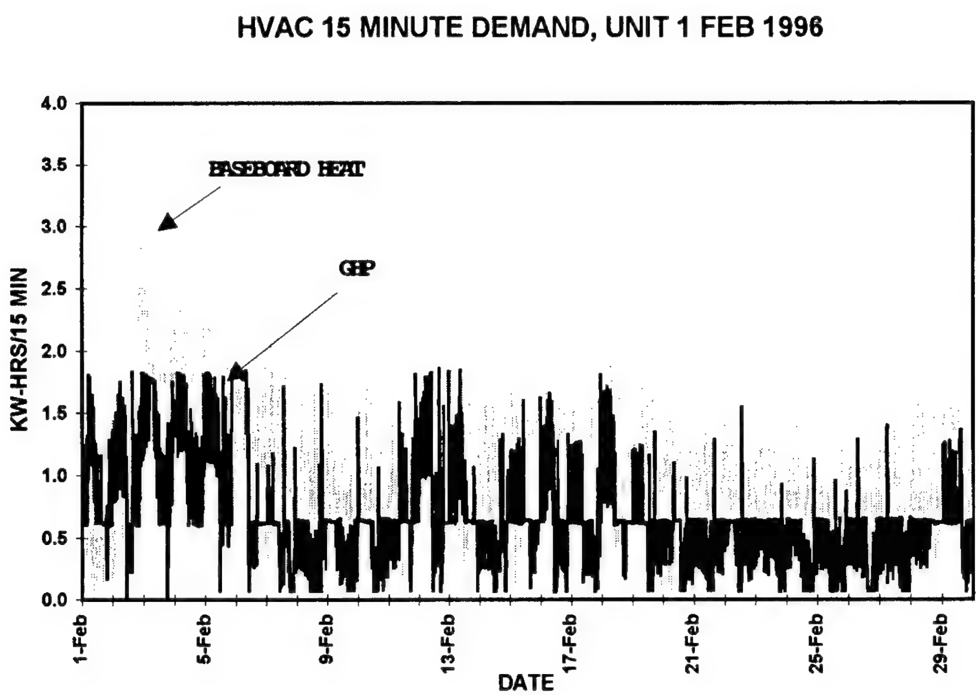

Figure 29. Peak HVAC demand for unit 1 GHP and resistance heat homes

Finally, the baseboard resistance heaters in the Selfridge homes are located along the outside walls and each room is zoned with its own thermostat. This arrangement avoids heating of unoccupied spaces and may provide comfort at a lower interior air temperature due to radiant heat effects.

The energy demand characteristic of the unit 1 GHP is compared to its adjoining resistance heat unit during a peak loading month (February, 1996) in Figure 29. As was the case with the Ft. Hood installation, a significant reduction in peak energy demand (approx. 40 % reduction in this month) is observed. The GHP demand curve, incidentally, clearly indicates two power levels corresponding to the compressor operating alone (peak of .6 kW-hrs/15 min) and the compressor plus strip heat (peak of 1.8 kW-hrs/15 min)

Design Improvements

One of the principal findings of the test program was the significant energy lost through the ducts in this installation. Reducing the duct losses would significantly reduce the use of the auxiliary strip heaters and the overall thermal load on the heat pump system. Indeed, we do not recommend replication of this installation without improvements to the ductwork insulation.

Adding insulation to the attic ductwork is not a simple task due to the limited attic space. One possibility would be to use flatter and wider supply and return ducts with enough ceiling to roof clearance to cover them with blown attic insulation. This should only be done in conjunction with a careful inspection of duct joints prior to covering the ductwork with insulation. Another possibility would be to route the ducts into the home interior by installing a drop ceiling chase near the center of the home.

The loop and heat pump sizing is adequate for the test homes. The loop temperature variations, although greater than expected by the designer, are still in a range which allows the GHP to provide high energy efficiency and capacity. At sites in the area without groundwater saturation, the freezing effect observed in this test would not occur and significantly lower loop temperatures would be likely.

GHP cost effectiveness at Selfridge

The GHP's installed at Selfridge provide excellent energy savings and the additional feature of summer air conditioning. But, in spite of this impressive performance, the cost of installing the GHP's cannot be recovered quickly through maintenance and energy savings. This is because the baseboard heat also has minimal maintenance costs and is not currently in need of replacement.

The contract cost for the modifications to the Selfridge homes was approximately 10K per home, including landscaping repairs, a $500 per home utility rebate given to the contractor, and the approximate contractor value of the donated WaterFurnace GHP's. This is very close to the contracted costs for the Ft. Hood installation. However, the Selfridge installation involved much more difficult drilling and duct fabrication and installation. It does not seem reasonable to assign a "production" subdivision conversion cost similar to Ft. Hood's, i.e. $5000 per unit. A crude estimate is offered of

$8000. per unit which assumes that a subdivision scale conversion would lead to some economies of scale.

The HVAC savings measured for the two year test period on the three test units are given in Table 8 in terms of percentages and absolute dollars. Because the GHP's offer air conditioning which is not supplied in the conventional homes, only the winter HVAC savings are considered in calculating the average savings. The average measured winter savings of the three test units is $262.

	UNIT 1	UNIT 2	UNIT 3
WINTER	32%	43%	34%
SUMMER	-112%	4%	21%
ANNUAL	16%	38%	32%
AVE ANNUAL HVAC $ SAVED	$115	$332	$271
WINTER HVAC $ SAVED	$212	$327	$248

Table 8. Measured savings of the GHP's relative to the baseboard resistance heat

The payback time for the GHP's depends on the replacement scenario. The current baseboard resistance heat units are not in need of replacement and have a very long service life. The cost of upgrading to GHP's would be simply the "production" cost of the conversion which we estimate at $8000. per home. This option has a slow simple payback over 30 years, based on annual savings of $262.

The payback is somewhat faster if it is assumed that the ductwork could be modified at negligible cost to eliminate the duct losses. For this case, we estimate that the winter savings relative to baseboard resistance heat would be 60% rather than the lower percentages given in Table XX. This calculation indicates average winter savings of $430, and the simple payback time is reduced to 18.6 years.

Summary and Concluding Remarks

The demonstrations at both Ft. Hood and Selfridge indicate that closed-loop GHP systems fit in comfortably with typical military family housing neighborhoods and can yield direct HVAC energy savings approaching 40%. The savings occur with increased or equivalent home comfort levels with systems that are transparent to the residents. The two sites tested have vastly different weather conditions indicating that the GHP concept can work well in both heating and cooling dominated climates. Clearly, any DoD establishment interested in reducing their energy consumption for space conditioning should seriously consider the use of GHP systems.

While the two demonstrations showed impressive savings, they also indicated that conditions at the individual sites have a strong influence on the ease and cost of GHP installation. The Ft. Hood site was definitely a more straightforward installation because the homes had serviceable existing ductwork and the relatively easy drilling conditions in Killeen. The Selfridge ductwork addition needed for the installation proved to be difficult, costly, and had thermal losses which reduced the energy savings for heating significantly.

The data acquisition systems at both sites worked well for the two year period of these tests and offer much detail on how the GHP systems behaved.. These data showed that the systems performed about as designed, although deviations from design performance were observed at both sites. The data suggest a few design changes which would be beneficial if any further installations are considered at these sites.

While the energy savings measured are impressive in terms of percentages, the relatively low utility rates on these bases and the high cost of installing GHP systems yields a slow (15-20 years) simple payback from energy savings for this conversion. This conclusion is similar to one reached from a recently published extensive measurement program on a large scale (4000 unit) GHP conversion project at Ft. Polk, LA [6]. This does not mean that such conversions are not desirable. Factors which may counter the slow energy cost payback can be reduced future maintenance costs offered by newer GHP equipment, future inflation in utility rates, and benefits of other incentives offered by the DoD or utilities aimed at saving energy or reducing peak demand.

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